Application Report
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Revised Pulsoximeter Design Using the MSP430

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ABSTRACT

This application report describes the upgrades and modifications made to the application discussed in *A Single-Chip Pulsoximeter Design Using the MSP430* (SLAA274). The improvements include the upgrade from RS232 connectivity to USB Bridge, provision for wireless interface, LCD upgrade and so on. And, the modifications include the hardware and software changes made to the previous design for better performance in terms of current consumption. A detailed current consumption analysis of the pulsoximeter board along with the current profile has also been discussed in this document. A custom LabVIEW GUI has been developed for this application to display the heart signal, heart rate and % SaO2 number. All the necessary files and steps to get this GUI up and running have been provided along with this report.

Related software and additional files (described in Appendix A) can be downloaded from http://www.ti.com/lit/zip/slaa458.

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1 Introduction

The objective of this document is to discuss the changes made to the pulsoximeter application in *A Single-Chip Pulsoximeter Design Using the MSP430* (SLAA274) [1] and to give a detailed description of how to get the modified version of the pulsoximeter application up and running. The pulsoximeter design using MSP430FG437 in SLAA274 has been improved by upgrading the existing features and by providing additional functionalities to the application.

This document discusses about the various hardware features, on-board interfaces and functionalities of the new pulsoximeter demo board. It also gives a detailed description of the different hardware and software requirements, and procedures needed to run the pulsoximeter application in conjunction with a customized LabVIEW GUI application. Also, a detailed description of the current consumption of the board has been presented.

2 Pulsoximeter Revisited

Modifications and additions are made to the pulsoximeter design in [1] to upgrade the hardware and demo features of the application. Figure 1 shows a very high level block diagram of the new upgraded pulsoximeter design.

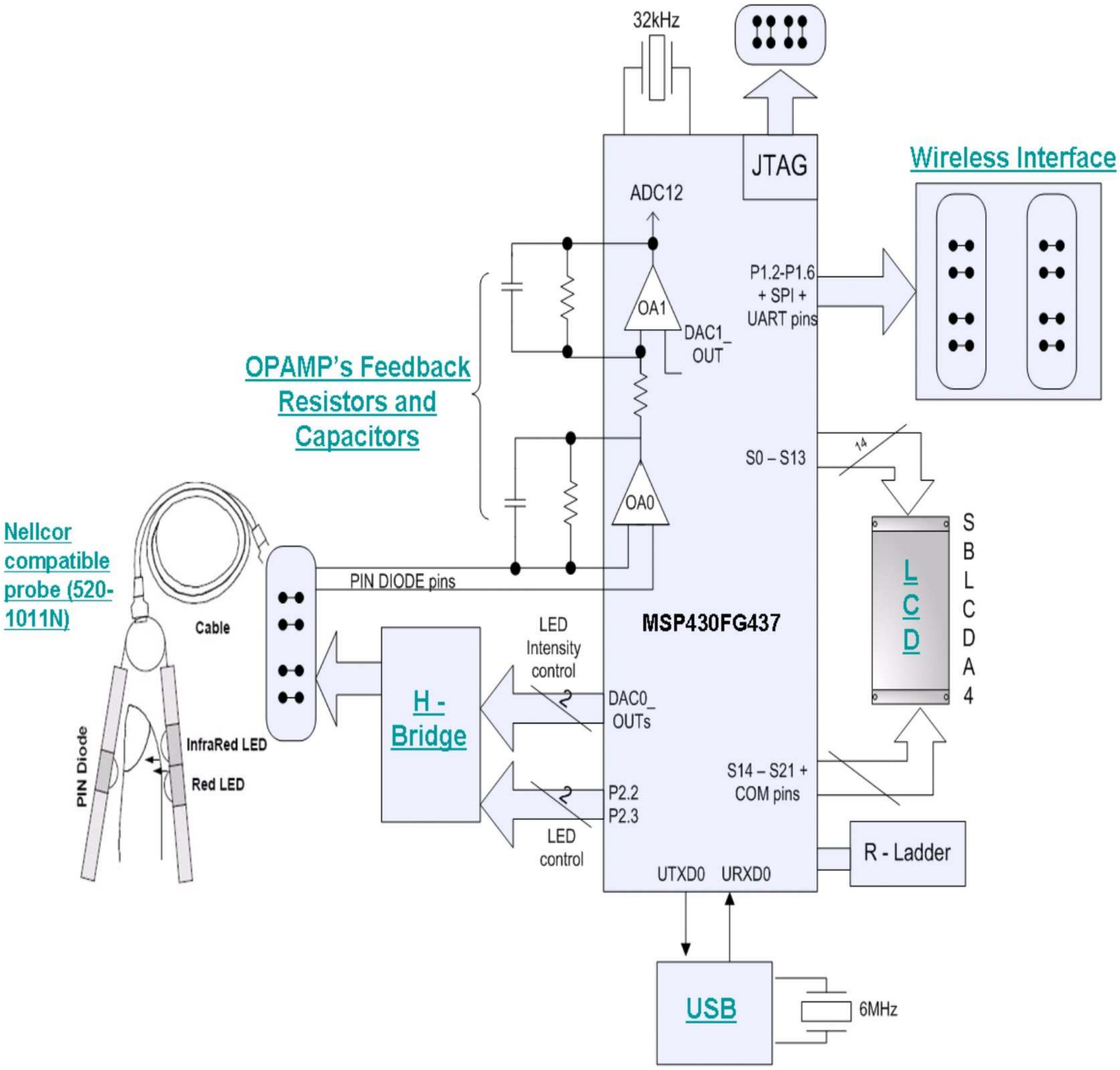

Figure 1. Revised Pulsoximeter Block Schematic

For more information regarding the basic operation of the single chip pulsoximeter application using the MSP430, see *A Single-Chip Pulsoximeter Design Using the MSP430* (SLAA274).

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Listed below are the major changes made to the pulsoximeter design presented in SLAA274:

- The RS-232 connection to target PC for serial data transfer has been replaced by USB connectivity.
- On-board options to interface with wireless world via headers supporting the CC11xx, CC2500, CC2420, CC2430 EMK boards, and the eZ430-RF2500T target boards from TI have been added.
- The LCD display in the previous design has been replaced by the SBLCDA4 LCD.
- A new LabVIEW GUI application has been developed to display the real time heart signal samples, heart rate and percentage oxygen saturation (SaO2) level captured by the board. This GUI application replaces the scope.exe GUI application provided with the old design.
- SaO2 look-up table generation.

In addition to the above changes, minor tweaks to the schematic are also implemented in the new design. All these topics are discussed in greater detail in the following sections.

2.1 Universal Serial Bus (USB)

The new pulsoximeter board is a USB-based medical instrument used for monitoring the heart rate and oxygen saturation level of a subject. The MSP430FG437 in the new pulsoximeter design supports the USB interface via its USART peripheral configured in UART mode for serial interface to target PC. An FTDI USB chip (FT232BM) has been used to provide the USB connection in this application.

The FT232BM device is a USB-to-asynchronous serial interface. It provides an asynchronous serial transmit and receive interface as well as modem control signals ready to interface to an asynchronous UART. The USB chip is easily interfaced to the MSP430 by using one of its internal UARTs. For more information regarding the USB circuitry design, refer the FT232BM data sheet and designer guide.[3] The following sections provide a brief description of RS232 to USB migration advantages, USB driver installation, serial data transfer to PC, and USB-bus power option.

2.1.1 Migration from RS-232 to USB Bridge Specification

Switching from RS-232 to USB link offers many advantages:

- USB is present on every new computer, not RS-232
- The final application can use the flexibility of the USB: data buffering, no data lost, automatic flow control, etc.
- USB link offers power supply for the application, thus simplifying the power management design and reducing the cost.
- USB automatic detection and configuration is an integral part of Windows Plug and Play technology, and this eliminates the laborious and error-prone procedure of manual setup of the connection.

2.1.2 USB Driver Installation

The operating system on the target PC requires the USB drivers to recognize and install the USB device on the pulsoximeter board. The USB Virtual COM Port (VCP) driver must be installed on the PC the very first time an active USB serial cable is plugged into the circuit. VCP drivers cause the USB device to appear as an additional COM port available to the PC and application software can access the USB device in the same way as it would access a standard COM port.

The drivers for the FTDI USB chip are located at *Revised Pulsoximeter Application /USB Drivers/CDM 2.02.04 WHQL Certified*. For detailed driver installation details, see the *USB Driver Installation Guide* document in the *Revised Pulsoximeter Application* folder.

2.1.3 Serial Data Transfer

In this application, serial data is transferred to the target PC via the UART/USB link at a standard baud rate of 115200bps. The MSP430 UART is software-configured to transmit data at this rate. The infra-red AC heart signal sample (12-bit data) is saturated to a byte length (8 Most Significant Bits) and transmitted to the target PC every 2 ms. The heart rate and % SaO2 values are also transmitted every 2ms along with the infra-red heart signal sample and they require one byte each for their representation.

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Since three data bytes are transmitted every time, for synchronization purposes in the GUI application, at the beginning of the asynchronous transfer every 2ms, synchronization bytes 0x00 and 0xFF are first transmitted successively and then the pulsoximeter data is transmitted. The GUI software waits for the data sequence “0x00 0xFF” and only after the data received matches the sequence, the bytes that follow are recognized as the actual data bytes. The serial data transmit part of the code is as shown.

```
TXBUF0 = 0x00;                  // synchronization byte1 = 0x00
while (!(IFG1 & UTXIFG0));
TXBUF0 = 0xFF;                  // synchronization byte2 = 0xFF
while (!(IFG1 & UTXIFG0));
TXBUF0 = i;                     // Infra-red AC heart signal sample
while (!(IFG1 & UTXIFG0));
TXBUF0 = heart_rate_LSB;        // Heart Rate per minute
while (!(IFG1 & UTXIFG0));
TXBUF0 = SaO2_LSB;              // Percentage Oxygen saturation
```

2.1.4 USB-Bus Power Option

The hardware in the previous design could either be FET powered or battery powered. In this revised design, the power options for the board are extended and made more power efficient by including the USB-bus power option. In the USB-bus power mode, the FT232BM is configured to interface with the 3-V logic MSP430. The USB chip requires 5V power and that is supplied by the USB cable. In addition to this, the USB connection supplies power to the entire board including the MSP430 via a low-dropout (LDO) regulator. In this design, a discrete 3-V LDO regulator (TPS71501) is used to supply the 3-V power to MSP430 logic from the USB bus power. The output of the 3-V regulator is also connected to the V_{CCIO} pin of the FT232BM to drive the UART interface I/O pins between the USB and MSP430 at the 3-V level.

The power configuration is designed such that the USB chip can only be USB bus-powered. This way, the USB circuitry is not turned ON when battery powered. Jumpers are used to select the power source for the pulsoximeter board. Detailed power configuration description of the new pulsoximeter board is discussed in the *Power Supply Configuration* document present in the *Revised Pulsoximeter Application* folder.

2.2 Chipcon Wireless Evaluation Module Interface

To make the application wireless, the MSP430 needs to interface to some of the existing transceivers. As discussed previously, an on-board option has been provided to interface with the wireless world via the pin headers supporting the CC11xx, CC2500, CC2420, CC2430 EMK boards and the eZ430-RF2500T target. These devices are low-cost, single chip transceivers equipped with serial interfaces that can be used to directly communicate with the MSP430. The transceiver modules CC11xx, CC2500, CC2420, CC2430 EMK and eZ430-RF2500T target boards are connected to the USART/SPI pins of the MSP430FG437. The eZ430-RF2500T target is also connected to the USART/UART pins of the MSP430FG437. The UART Tx and Rx lines are routed directly to the eZ430-RF 6-pin header and via jumpers to the USB circuitry.

2.3 LCD Display

The LCD in the previous design has been replaced by the SBLCDA4 LCD. This includes both software and hardware modification.

The integrated SoftBaugh SBLCDA4 LCD display supports 4-MUX operation and interfaces to the LCD driver peripheral of the MSP430FG437. S0-S22 pins of the MSP430FG437 drive the LCD segments and an equally weighted R-Divider ladder between R33-R03 pins that establish the required analog levels to drive the LCD signals. More information on the LCD can be obtained from the manufacturer's data sheet.[4] Both the heart rate and the %SaO2 numbers are displayed on this LCD.

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2.4 LabVIEW PulseOx Monitor GUI

A customized LabVIEW GUI application has been developed to display the heart signal samples on the PC. There is no need to install LabVIEW to run the Pulsox GUI application. The users only need the LabVIEW Run-Time Engine or the stand-alone executable to run the PulseOx GUI on a PC.

Figure 2 shows a screen shot of the GUI with heart signal samples displayed in the waveform chart.

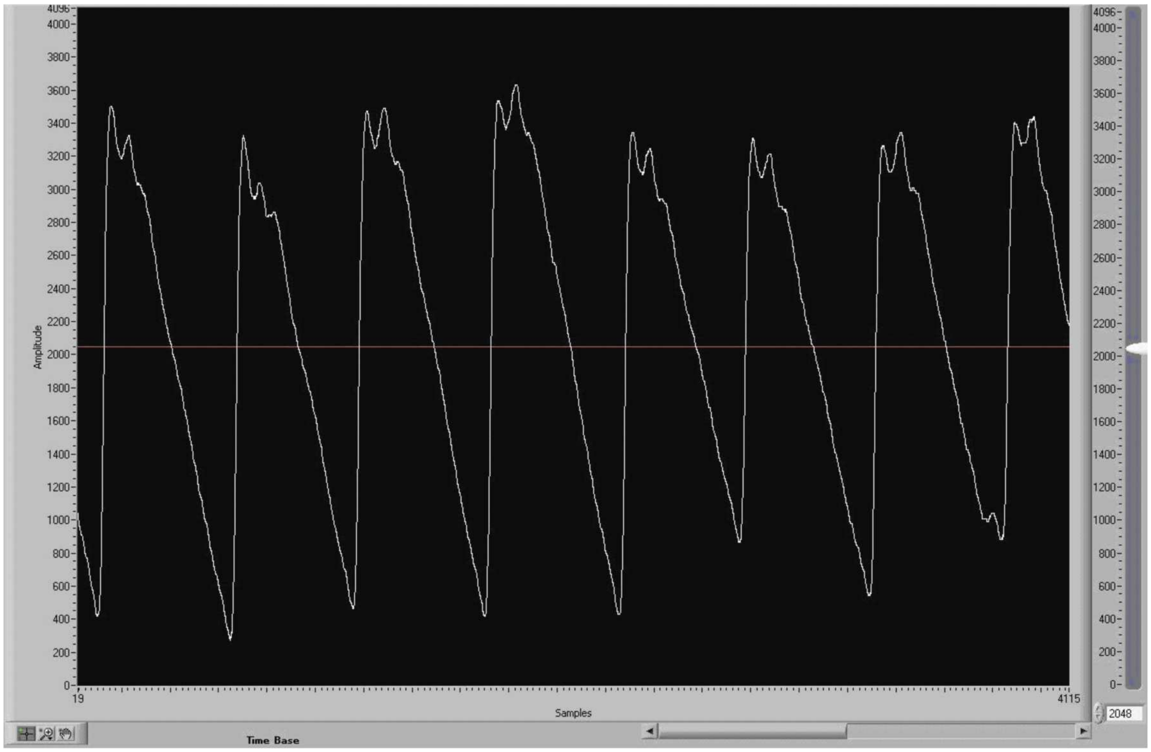

Figure 2. Heart Signal Output

LabVIEW stand-alone applications include executable files that are distributed to users. However, these executables produced by the application builder (in LabVIEW) are not truly standalone in that they also require that the LabVIEW run-time engine to be installed on the target computer on which users run the application. Therefore, the user requires the LabVIEW run-time engine to run the stand-alone executable. The LabVIEW run-time engine helps load and run LabVIEW VI.

This GUI application is different from the scope.exe GUI application that is provided along with the application report SLAA274. It's a lot simpler to get the GUI running and it eliminates the protracted and error prone process of running the application from the command prompt. See the *Demo – PulseOx Monitor* document for the step-by-step explanation of running the PulseOxMonitor GUI application. The document is present in the Revised Pulsoximeter Application zip folder.

2.5 SaO2 Look-Up Table Generation

This is a software modification made to the C code *oximeter_ext_probe_1.c*. A SaO2 look-up table that defines the relationship between the ratio R and %SaO2 values was first generated by extrapolating values from the “Empirical and Theoretical Ratio (R) to SaO2” curve [1], and then verified by taking two sets of readings of few subjects – first the correct SaO2 values from an actual pulsoximeter equipment (a Masimo instrument) and then the Ratio values (R) from the pulsox board.

Most of the SaO2 values generated this way were concentrated towards the 90%-100% range. So the percentage oxygen saturation values that are displayed are an approximate measure of the percentage SaO2 levels in the normal range.

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2.6 MSP430GF437 Pulsoximeter Schematic Changes

Minor tweaks have been made to the old pulsoximeter schematic shown in SLAA274 to get the pulsoximeter demo to function efficiently. These changes with necessary explanation are:

- R and C values of transimpedance amplifier (OA0)

  Initially when the feedback resistor and capacitor values of the transimpedance amplifier were R_F = R10 = 5.1 MΩ and CF = C7 = 3 pF, respectively (on the new board), the output of the amplifier had a low frequency noise associated with it. Replacing the R_F = R10 value from 5.1 MΩ to 500 kΩ removed the low-frequency noise in the amplifier's output signal. This can be explained thus: a feedback capacitor C_F is added to the transimpedance amplifier (op amp with only the feedback resistor connected) to remove the instability caused by the input capacitance of the op amp and its circuitry. The value of the feedback capacitor is calculated using Equation 1.

  $$C_F = \sqrt{\frac{C_S}{GBW \times R_F}} \tag{1}$$

  Where,

  C_F = feedback capacitance

  C_S = input capacitance of the op amp (OA0)

  GBW = gain bandwidth product of OA0

  R_F = feedback resistor

  According to Equation 1 with C_F = 3 pF, GBW = 2.2 MHz [5], and C_S = 10 pF, the feedback resistor value is R_F ≈ 500 kΩ.

- Resistor divider ladder

  The voltages required for the LCD signals are supplied externally to pins R33, R23, R13, and R03. Using an equally weighted resistor divider ladder between these pins establishes the analog voltages. In the previous design, these resistor values were 300 kΩ (R10, R11, R12). However, the *MSP430x4xx Family User's Guide* recommends that the resistor value R of the resistor divider typically be 680 kΩ. [2] Accordingly, the R value has been changed from 300 kΩ to 680 kΩ (R15, R16, R17) in the new schematic. Changing the resistor values to 680 kΩ also helps reduce the current consumed by the LCD module. The resistor from pin R03 to GND which controls the LCD contrast remains the same, as in the previous design.

- Connection of $\overline{\text{RST}}$/NMI pin

  The *MSP430x4xx Family User's Guide* recommends a 47-kΩ pullup with 10-nF pulldown connected to the $\overline{\text{RST}}$/NMI pin. [2] Therefore, the R and C values connected to the $\overline{\text{RST}}$/NMI pin in the old design (R15 = 100 kΩ, C8 = 0.1 µF) have been changed to the user's guide specified values in the new design (R5 = 47 kΩ, C1 = 10 nF).

- Low pass filtering at DV_{CC} and AV_{CC} pins

  In the previous design, a simple RC low pass filter was implemented at the DV_{CC} and AV_{CC} pins. A resistor value of R = 100 Ω was used between the V_{CC} line and the DV_{CC} and AV_{CC} pins. Depending on the total current consumed by the MSP430, a significant voltage drop from the actual V_{CC} level would occur at the DV_{CC} and AV_{CC} pins. This may affect the normal operation of the MSP430. Therefore, in the new design, the 100-Ω resistor between V_{CC} and DV_{CC} has been removed, and a 0-Ω resistor has been placed between the V_{CC} and AV_{CC} lines.

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3 Current Consumption

This section of the document discusses about the various steps taken to optimize the over-all current consumption of the pulsoximeter board, current profile for various cases, and current modes during which different sets of peripherals are active.

3.1 Current Optimization

Hardware and software modifications have been made to the previous pulsoximeter design in order to reduce the over-all current consumption of the board. These changes are as listed below:

- Hardware modifications

  Base resistors (R29 and R30) are added between the base of PNP transistors Q1 and Q2 and the MSP430 port pins P2.2 and P2.3, respectively. These base resistors are required to limit the current flowing into the base of the transistor. The resistor values are chosen sufficiently low to ensure that the transistor is thoroughly saturated. Reducing these resistor values increase the amplitude of the heart signals as seen on the PC and also increase the overall current consumption of the board.

- Software modifications

  The ADC12 module in the pulsoximeter application is configured to be triggered by the rising edge of the TimerA1 signal which has a period of 1ms. This implies that the OFF time of the Timer A1 represents the period when the H-Bridge and the corresponding LED in the sensor are ON. In SLAA274, the duty cycle of the Timer A1 signal was ~34% (with TACCR0 = 31 and TACCRI = 20 in Set/Reset output mode). Software modification has been made such that the duty cycle of the TimerA1 signal has been increased from 34% to ~69% (with TACCR0 = 31 and TACCR1 = 10 in Set/Reset output mode), taking into account that this time sufficient for the analog signal chain to settle before any measurement is taken. This decreases the ON time of LEDs (infra-red and visual red) from ~0.7 ms to ~0.4 ms. And, reducing the ON time of LEDs every 1 ms, helps reduce the over-all current consumption of the board significantly.

3.2 Current Consumption Profile

As discussed earlier, the pulsoximeter board can be locally powered either by USB bus power or two AAA batteries. Current consumption of the board is not an issue when it is USB bus powered. Therefore, all the current measurements, which are presented in this section, have been made with the board being battery powered and these current numbers do not include the power consumed by the USB circuitry.

The CPU operation in the pulsoximeter application can be broadly classified into two modes; infra-red (IR) LED operation and visual red (VS) LED operation. The CPU enters these modes sequentially every 2 ms. During each mode, the CPU along with the corresponding LED and various peripherals are active for ~0.4 ms and then go into low-power mode with both the LEDs OFF for the rest of the period (~0.6 ms).

The four-transistor H-Bridge is a variable gain circuit that turns the LEDs ON and OFF, and this arrangement consumes a significant portion of the total current consumed by the board (discussed in detail in Section 3.2.1). The current consumed, however, depends on the DAC0 output that is used to turn ON the NPN transistors. The DAC0 output controls the light intensities of the LEDs such that they are well within the pre-determined target range. The light intensity control is done in software by comparing the LED light intensities previously sampled with the target high and low thresholds [FIRST_STAGE_TARGET_HIGH and FIRST_STAGE_TARGET_LOW, respectively (see sample code)]. If the LED intensity is out of the target range, fine or coarse step counts are used to bring the LED intensity back in the right direction. The DAC0_DAT register is then loaded with appropriate data. The LED light intensities should be considerably high, because weak signals give poor results in later stages.

Because the value of the DAC12_0DAT register changes depending on the previously sampled data points, the current consumption of the pulsoximeter board is not the same at all times. For the ease of current consumption computation, the operation of the 4-transistor H-Bridge can be classified into two cases (Case 1 and Case 2). These cases represent the two extreme H-Bridge current consumption scenarios:

- Case 1 refers to the scenario when DAC12_0DAT = 0x047E, which implies, V_{Th} of the NPN transistor = 0.7 V (V_{ref} = 2.5 V) and minimum current flows through the ON-path of the H-Bridge circuitry.
- Case 2 refers to the scenario when DAC12_0DAT = 0x0FFF and maximum current flows through the ON-path of the H-Bridge circuitry.

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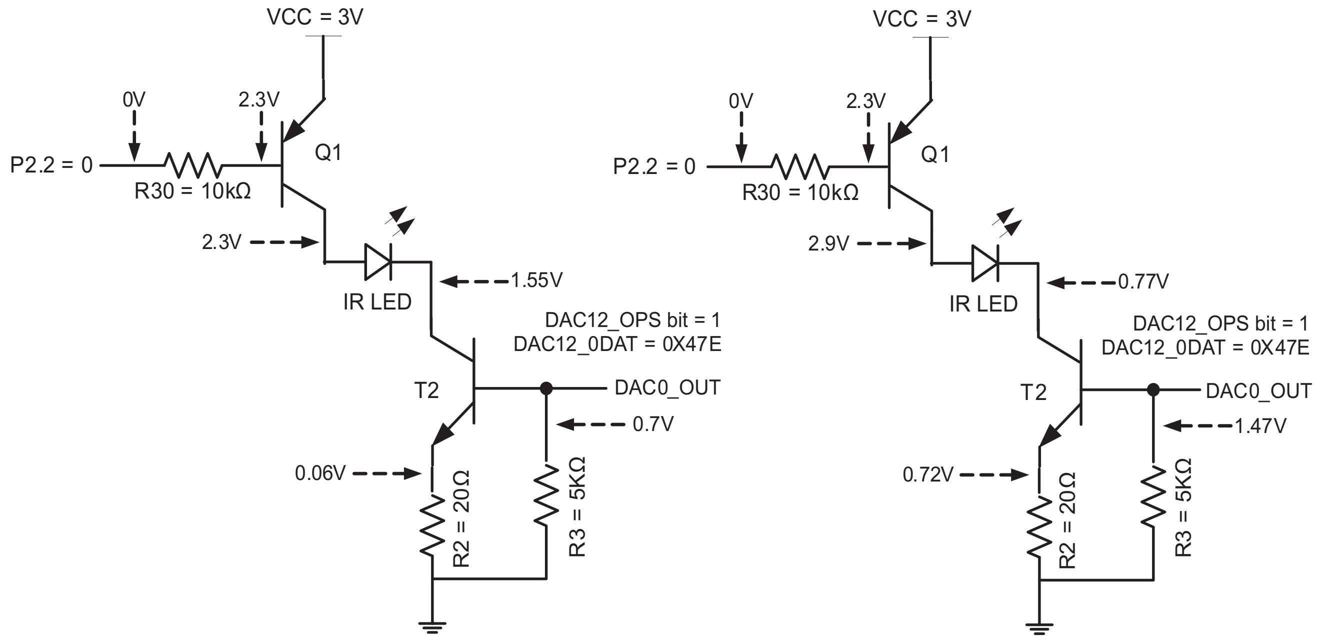
Case 1 and Case 2 being the extreme current consumption cases for the H-Bridge circuit, the current consumption of the board will always be between the current numbers seen in the two cases. Section 3.2.2 gives a detailed description of the current consumption profiles for the two cases.

NOTE: The ON path of the H-Bridge circuit comprises either the PNP transistor Q1 – IR LED – NPN transistor T2 or the PNP transistor Q2 – VS LED – NPN transistor T1.

3.2.1 H-Bridge Current Consumption

This section gives a detailed description of the ON-path configuration and the current consumption of the four transistor H-Bridge circuit with either IR or VS LED ON, for both the cases. It can be seen that H-Bridge circuit consumes significant amount of the total board current.

Figure 3 shows voltage levels of the ON-path of the H-Bridge when IR LED in ON for Case 1 and Case 2.



a. IR LED ON – Case 1 **b. IR LED ON – Case 2**

Figure 3. Typical H-Bridge Current Consumption with IR LED ON for (a) Case 1 (b) Case 2

Table 1 gives an approximate estimate of the total current consumed by the H-Bridge circuitry based on Figure 3.

Table 1. H-Bridge Current Consumption With IR LED ON

Case 1		Case 2	
Current Path	**Current Consumed**	**Current Path**	**Current Consumed**
Q1 – IR LED – T2	$\frac{0.06\text{ V}}{20\ \Omega} = 3\text{ mA}$	Q1 – IR LED – T2	$\frac{0.72\text{ V}}{20\ \Omega} = 36\text{ mA}$
Base of Q1 – R30 – P2.2	$\frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$	Base of Q1 – R30 – P2.2	$\frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$
Base of T2 – R3 – GND	$\frac{0.7\text{ V}}{5\text{ k}\Omega} = 0.14\text{ mA}$	Base of T2 – R3 – GND	$\frac{1.47\text{ V}}{5\text{ k}\Omega} \cong 0.3\text{ mA}$

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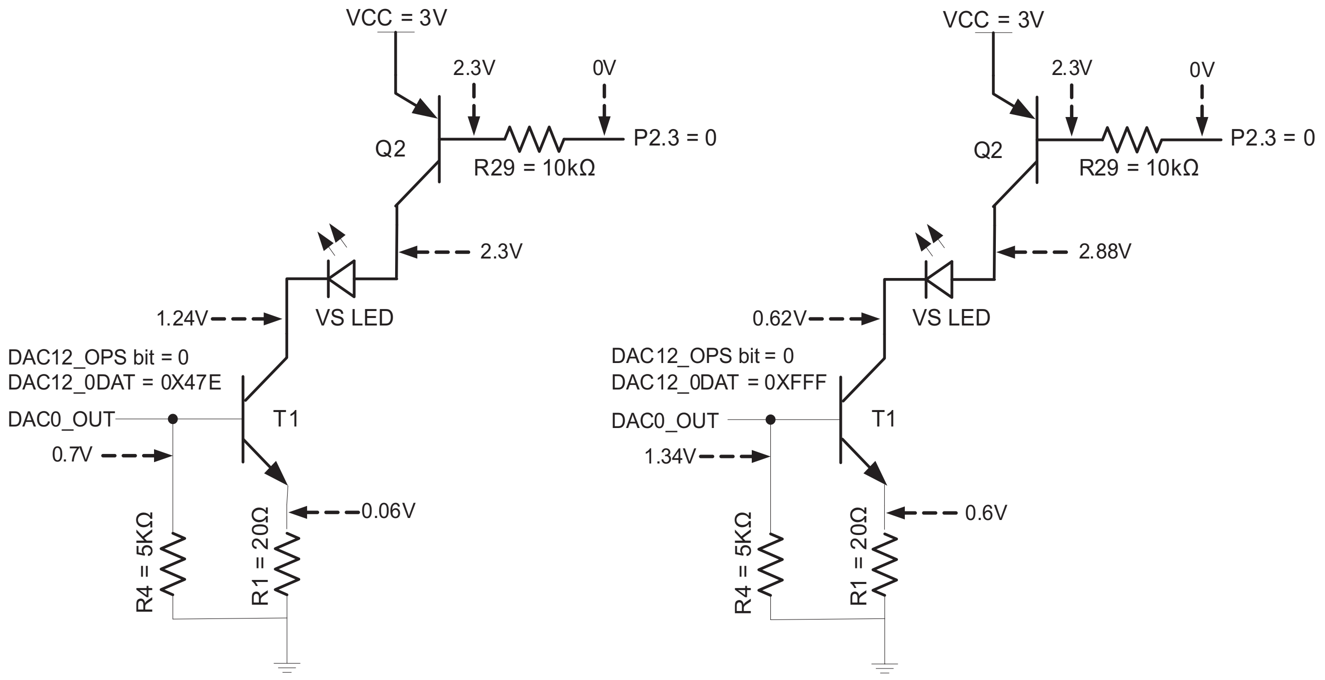
Figure 4 shows voltage levels of the ON-path of the H-Bridge when VS LED in ON for Case 1 and Case 2 respectively.



a. VS LED ON – Case 1

b. VS LED ON – Case 2

Figure 4. Typical H-Bridge Current Consumption with VS LED ON for (a) Case 1 (b) Case 2

Table 2 gives an approximate estimate of the total current consumed by the H-Bridge circuitry based on Figure 4.

Table 2. H-Bridge Current Consumption With VS LED ON

Case 1		Case 2	
Current Path	**Current Consumed**	**Current Path**	**Current Consumed**
Q2 – VS LED – T1	$\frac{0.06\text{ V}}{20\ \Omega} = 3\text{ mA}$	Q2 – VS LED – T1	$\frac{0.06\text{ V}}{20\ \Omega} = 3\text{ mA}$
Base of Q2 – R29 – P2.3	$\frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$	Base of Q2 – R29 – P2.3	$\frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$
Base of T1 – R4 – GND	$\frac{0.7\text{ V}}{5\text{ k}\Omega} = 0.14\text{ mA}$	Base of T1 – R4 – GND	$\frac{1.34\text{ V}}{5\text{ k}\Omega} \cong 0.27\text{ mA}$

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3.2.2 Current Consumption Profiles

This section discusses about the current consumption profiles for two H-Bridge extreme scenarios, Case 1 and Case 2. The two LEDs (IR LED and VS LED) are time multiplexed at 500 times per second with the help of Timer A0, which interrupts the CPU every 2 ms, to initiate the sequence of operations; IR LED operation and VS LED operation.[1] Various tasks are performed during each of these LED operations and they have been discussed in greater detail in the following sub-sections.

Figure 5 shows a typical current consumption and timing profile of the pulsoximeter board for Cases 1 and 2. The IR LED and VS LED operations are exactly the same in both the cases. However, the significant differences between Case 1 and Case 2 that are to be noted here are the current consumption numbers (I_{CC}) during active mode 1 (AM1_IR and AM1_VS) and the voltage level of the DAC0 output signal (DAC12_0OUT). Case 1 and Case 2 waveforms for the DAC12_0OUT vs time and I_{CC} vs time plots can be differentiated by the line patterns shown below.

— —	**CASE1**
——	**CASE2**

In Case 1, the DAC output is ~0.7 V (DAC12_0DAT = 0x47E), and the current consumed during active modes AM_IR and AM_VS are equal, and is approximately 7 mA (typical). On the other hand, in Case 2, the DAC output is driven to 2.5 V (DAC12_0DAT = 0xFFF), and the current consumed during AM_IR and AM_VS are different and is approximately 41 mA and 34.5 mA (typical), respectively.

NOTE: The DAC1 output is used to provide a reference voltage level to positive input of OA0, which acts as a transimpedance amplifier and changing the contents of the DAC1 data register does not have any significant impact on the current profile. Therefore, the DAC1 data register is loaded with the same value (0x07D0) in both the cases.

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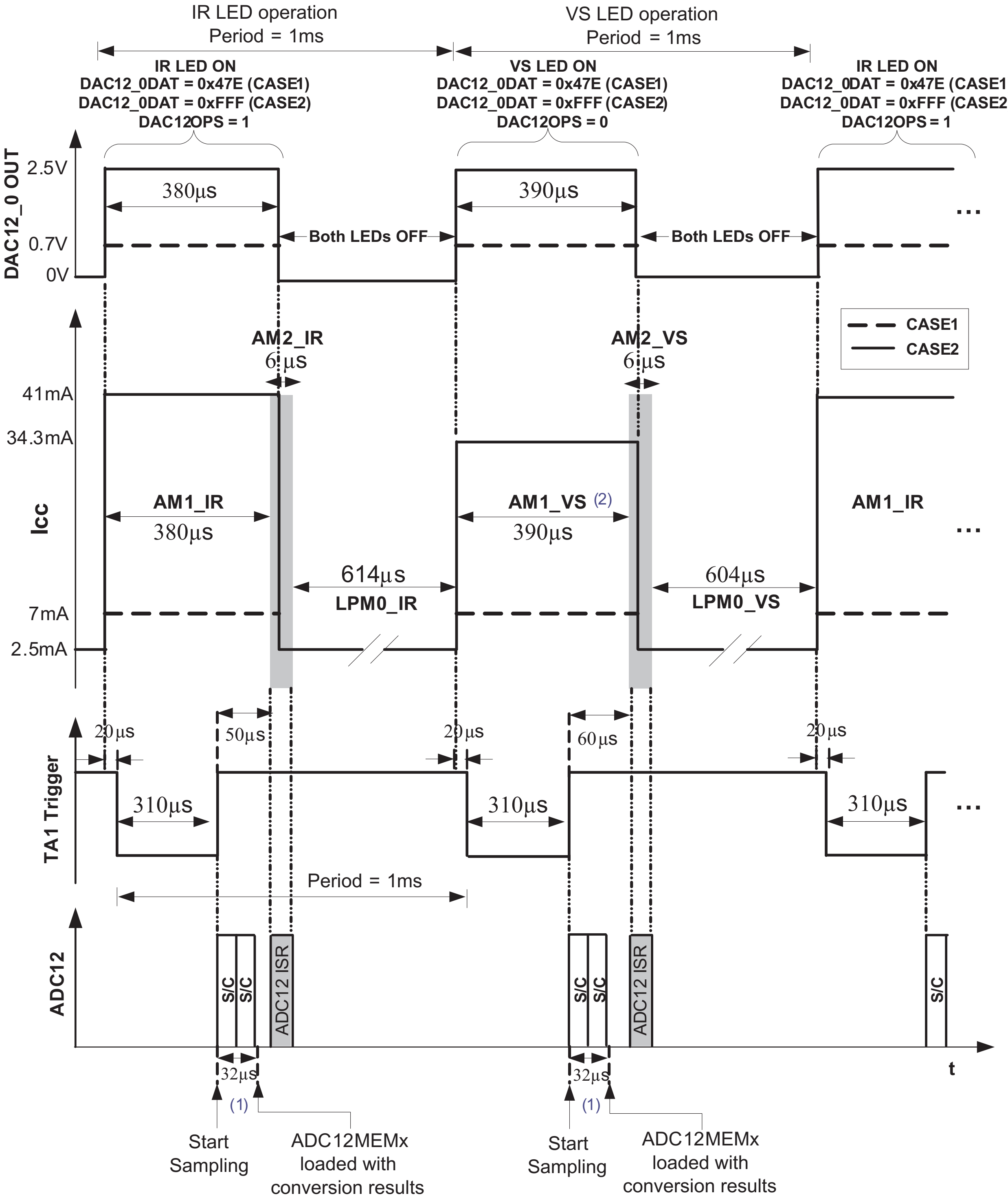

NOTE: 1. With ADC12CLK = internal ADC12 oscillator = ~5MHz [5], sampling time = 64 ADC12CLK cycles, the time taken to make a single conversion = (64 + 13) / 5 MHz ≈ 15.4 µs. Therefore, for a sequence of two conversions, it takes ~32 µs for the ADC12MEMx registers to be loaded with the conversion results.

NOTE: 2. The time period AM1_VS does not include the time required to transmit the 5bytes (synchronization + data bytes) via UART.

Figure 5. Typical Current Consumption and Timing Profile

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3.2.2.1 IR LED Operation

As shown in Figure 5, the IR LED operation comprises of the AM1_IR (Timer A0 ISR), the AM2_IR (ADC12 ISR) and the LPM0 mode, in the same order. In the IR LED operation: (1) the IR LED is turned ON (in Timer A0 ISR) to sample necessary signals in the analog chain and then tuned OFF (in ADC12 ISR) before going to the low power mode (2) the data sampled during the previous VS LED operation (AM1_VS) is read from the ADC12MEMx registers, processed and accumulated to compute % SaO2.

- During the IR LED operation, the CPU enters the Timer A0 ISR which is termed as Active Mode 1 in IR LED operation (represented as AM1_IR in the current profile) and performs the following steps:
  - The DAC12_0 output control bit DAC12OPS is set and P2.2 is driven low to enable the ON-path of the H-Bridge which comprises of transistors Q1 and T2. This configuration turns the IR LED ON and allows sufficient time for the analog signal chain to become stable before sampling.
  - The sampled and converted data obtained from the previous VS LED operation is read from the ADC12MEMx registers.
  - The VS conversion data is further processed to (1) extract only the ac components of the signal for %SaO2 computation (2) track the DC component associated with the signal and update the DAC12_1DAT register and in-turn the voltage offset of OA1 (3) ensure the LED intensity is within the target range so that it can be handled properly in the next sequence.

  The CPU is in the AM1_IR mode for ~0.38 ms and during this time the Timer A1 triggers the ADC12 sampling. ADC12 is configured to sample two channels (A1 – OA0 output and A3 – OA1 output) in a single sequence mode. The ADC12 takes around 32µs to complete the sequence of conversion and with the ADC12IFG flag set, it waits for the CPU to exit Timer A0 ISR.
- After exiting the Timer A0 ISR (AM1_IR), the CPU enters the ADC12 ISR which is termed as the Active Mode 2 in IR LED operation (represented as AM2_IR in the current profile). The CPU is in the AM2_IR mode for ~6 µs during which the following steps are executed:
  - The DAC12_0DAT register is cleared and the P2.2 port pin is set to force a logic high output. This turns OFF the transistors Q1 and T2 and in-turn the IR LED.
  - The DAC12_1DAT register is also cleared.
- With the IR LED switched OFF, the CPU enters Low Power Mode 0 (represented as LPM0_IR in the current profile) and waits there for ~614 µs until the Timer A0 interrupts the CPU to initiate the VS LED operation.

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3.2.2.2 VS LED Operation

The VS LED operation is very similar to the IR LED operation except that the VS LED is turned ON and OFF for the ADC12 to sample data and the processing of the conversions results of the previous IR LED operation are performed to compute both the heart rate and %SaO2. Similar to IR LED operation, the VS LED operation comprises the AM1_VS (Timer A0 ISR), AM2_VS (ADC12 ISR,) and the LPM0 modes, in the same order.

- During the VS LED operation, the CPU enters the Timer A0 ISR which is termed as Active Mode 1 in VS LED operation (represented as AM1_VS in the current profile) and performs the following steps:
  - The DAC12_0 output control bit DAC12OPS is reset and the P2.3 is driven low to enable the ON-path of the H-Bridge which comprises of transistors Q2 and T1. This configuration turns the VS LED in the sensor ON and allows sufficient time for the analog signal chain to become stable before sampling.
  - The sampled and converted data obtained from the previous IR LED operation is read from the ADC12MEMx registers.
  - The IR conversion data is further processed to (1) extract only the ac components of the signal for heart rate computation and %SaO2 computation (2) track the DC component associated with the signal and update the DAC12_1DAT register and in-turn the offset voltage of OA1 (3) ensure the LED intensity is within the target range so that it can be handled properly in the next sequence.

  Unlike the AM1_IR mode, the AM1_VS mode performs additional tasks, such as detect a heart beat and compute the heart rate, and therefore the CPU remains in AM1_VS mode for a longer time compared to the AM1_IR (typically 10 µs longer). In the VS LED operation, the CPU is in AM1_IR mode for typically ~0.39 ms and during this time the Timer A1 triggers the ADC12 to start sampling. ADC12 is configured to sample two channels (A1 – OA0 output and A3 – OA1 output) in a single sequence mode. The ADC12 takes approximately 32 µs to complete the sequence of conversion and with the ADC12IFG flag set, it waits for the CPU to exit Timer A0 ISR.
- After exiting the Timer A0 ISR (AM1_VS), the CPU enters the ADC12 ISR which is termed as the Active Mode 2 in VS LED operation (represented as AM2_VS in the current profile). The CPU is the AM2_VS mode for ~6 µs during which the following steps are executed:
  - The DAC12_0DAT register is cleared, and the P2.3 port pin is set to force a logic high output. This turns OFF the transistors Q2 and T1 and in turn the VS LED.
  - The DAC12_1DAT register is also cleared.
- With the VS LED switched OFF, the CPU enters Low-Power Mode 0 (represented as LPM0_VS in the current profile) and waits for ~604 µs until the Timer A0 interrupts the CPU to initiate the VS LED operation.

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3.2.2.3 Current and Timing Considerations

Table 3 gives a list of all the peripherals that are ON during various modes of operation and the corresponding typical current consumption numbers for both Case 1 and Case 2. These peripherals are significant contributors to the overall current consumption during each stage.

Table 3. Significant Current and Timing Considerations

Current Mode/ Software Flow/ Important Actions	Peripherals ON	Current Consumption of the Board		ON Time
		Case 1 (DAC12_0DAT = 0x047E) (DAC12_1DAT = 0x07D0)	Case 2 (DAC12_0DAT = 0x0FFF) (DAC12_1DAT = 0x07D0)	
AM1_IR (Active Mode 1)/ Timer A0 ISR/ Infra-Red LED ON	H-Bridge (P2.2 = 0)[1], Internal 2.5V Vref+, OA0, OA1, DAC12_0, DAC12_1, ADC12[2], Timer_A ON	7 mA	41 mA	380 µs
AM2_IR (Active Mode 2)/ ADC12 ISR/ Infra-Red LED OFF	See [3]	7 mA / 2.5 mA	41 mA / 2.5 mA	6 µs
LPM0_IR/ Low Power Mode 0	Internal 2.5V Vref+, OA0, OA1, ADC12[2], DAC12_0, DAC12_1[4], Timer_A ON	2.5 mA	2.5 mA	614 µs
AM1_VS (Active Mode 1)/ Timer A0 ISR/ Visual-Red LED ON	H-Bridge (P2.3 = 0)[5], Internal 2.5V Vref+, OA0, OA1, DAC12_0, DAC12_1, ADC12[2], Timer_A ON	7 mA	34.3 mA	390 µs
AM2_VS (Active Mode 2)/ ADC12 ISR/ Visual-Red LED OFF	See [3]	7 mA / 2.5 mA	34.3 mA / 2.5 mA	6 µs
LPM0_VS/ Low-Power Mode 0	Internal 2.5V Vref+, OA0, OA1, ADC12[2], DAC12_0, DAC12_1[4], Timer_A ON	2.5 mA	2.5 mA	604 µs

[1] With P2.2 = 0 and DAC12_0OPS = 1, transistors Q1 and T2 are in saturation. Refer Figures 3a and 3b for detailed description of the ON-path configuration of the H-Bridge to turn on IR LED during both Case 1 and Case 2 scenarios.

[2] ADC12 is configured to sample input data in single sequence mode using the internal ADC12 oscillator, and the rising edge of Timer A1 signal is used to trigger each conversion. The ADC12 ON and enable bits in the ADC12CTL0 register are set almost all the time. However, the ADC12 core and the internal ADC12 oscillator are automatically disabled when not converting and re-enabled when needed [2].

[3] AM2_IR and AM2_VS represent the active modes when the device is in ADC12 ISR. During the ADC12 ISR, the DAC12_0DAT and DAC12_1DAT registers are reset and the port pins P2.2 or P2.3 (depending on which pin was reset in the previous mode – AM1) are set to force a logic high output. These instructions ensure that all four transistors of the H-Bridge and in-turn both the IR and VS LEDs are turned off, before entering the low power mode 0 (LPM0).

[4] Though the DAC12_xDAT = 0x0, the DACs are continuing to load the internal 2.5V reference (Vref+). The internal loading of the 2.5V Vref+ around 50uA per DAC12 module.

[5] With P2.3 = 0 and DAC12_0OPS = 0, transistors Q2 and T1 are in saturation. Refer Figures 4a and 4b for detailed description of the ON-path configuration of the H-Bridge to turn on VS LED during both Case 1 and Case 2 scenarios.

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3.3 Average Current Consumption

With the help of the ON times and current consumption numbers during different modes of operations for both Case 1 and Case 2 scenarios (see Table 3) the average current consumption for each of these cases can be computed:

- Case 1: $I_{avg} \approx (7 \text{ mA} \times 0.38 + 2.5 \text{ mA} \times 0.62) \approx 4.2 \text{ mA}$
- Case 2: $I_{avg} \approx (41 \text{ mA} \times 0.19 + 2.5 \text{ mA} \times 0.31 + 34.3 \text{ mA} \times 0.195 + 2.5 \text{ mA} \times 0.305) \approx 16 \text{ mA}$

Case 1 and Case 2 being the extreme current consumption scenarios, the current consumption at any time would be between 4.2 mA and 16 mA. The average current drawn by the pulsoximeter board is closer to Case 1 when there is no finger in the sensor (that is, when the board is powered up, but no finger is inserted into the finger sensor). Average current drawn is closer to Case 2 when there is a finger in the finger sensor and the pulsoximeter is measuring and displaying the heart rate and %SaO2 numbers on the LCD screen.

4 References

1. *A Single-Chip Pulsoximeter Design Using the MSP430* (SLAA274)

2. *MSP430x4xx Family User's Guide* (SLAU056)

3. www.ftdichip.com

4. SBLCDA4 data sheet (http://www.softbaugh.com/downloads/SBLCDA4_Specification.pdf)

5. MSP430FG437 data sheet (SLAS380)

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Appendix A Associated Files

The following files are included in the associated zip folder (http://www.ti.com/lit/zip/slaa458):

- Schematics

  The schematics of the new pulsoximeter design include the MCU.pdf and USB.pdf. As the names suggest, MCU.pdf is the MSP430FG437 design centric schematic and the USB.pdf contains the USB circuitry. The schematics are present in the folder *Revised Pulsoximeter Application/Schematics*.
- Code Files

  The code files for the new pulsoximeter design include revised_oximeter_ext_probe_1.c and mul_v4.s43 files that are present in the folder *Revised Pulsoximeter Application/Code*.
- Gerber Files

  The Gerber files of the new pulsoximeter board are present in the folder *Revised Pulsoximeter Application/Gerber Files*. The main files include:
  - component side = Pulsox-0.00.top
  - solder side = Pulsox-0.00.bot
  - silkscreen component side = Pulsox-0.00.slk
  - solder stop component side = Pulsox-0.00.smt
  - solder stop solder side = Pulsox-0.00.smb
  - excellon drill file = Pulsox-0.00.drd
  - tool list file = Pulsox-0.00.dri
  - outline = Pulsox-0.00.oln
- BOM

  The excel spread sheet Revised Pulsoximeter BOM.xls which consists of the BOM for the new pulsoximeter board is present in the *Revised Pulsoximeter Application* folder.
- Power Supply Configuration

  This document discusses the demo board power options and is present in the *Revised Pulsoximeter Application* folder.
- USB Drivers

  The drivers required for on-board USB device is present in the folder *Revised Pulsoximeter Application/USB Drivers/CDM 2.02.04 WHQL Certified*. Download these files to a location on the target PC during USB driver installation.
- USB Driver Installation Guide

  This document is a detailed driver installation guide for the on-board USB device under Windows XP and is present in the *Revised Pulsoximeter Application* folder.
- GUI Application

  The LabVIEW standalone executable and the LabVIEW Run-Time Engine are in the folder *Revised Pulsoximeter Application/Pulsoximeter PC Software/GUI Executable* and *Revised Pulsoximeter Application/Pulsoximeter PC Software/LabVIEW Run-Time Engine*, respectively. Download these files to a location on the target PC during the PulseOx Monitor Demo.
- Demo – PulseOx Monitor GUI

  This document serves as a guide to get the PulseOx Monitor GUI installed and running on a USB-equipped Windows PC and is present in the *Revised Pulsoximeter Application* folder.

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Appendix B Schematics

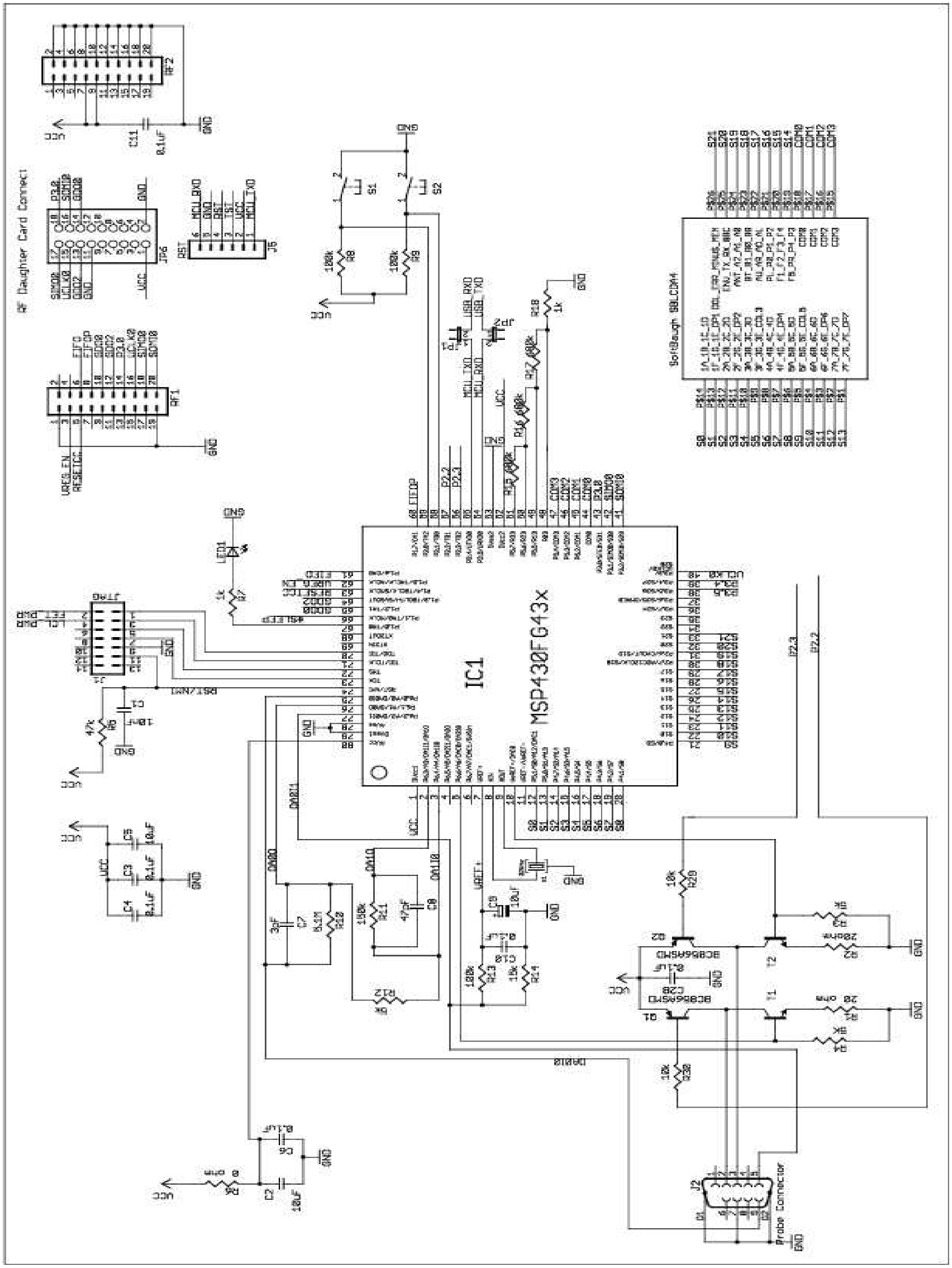

Figure 6. MCU Schematic

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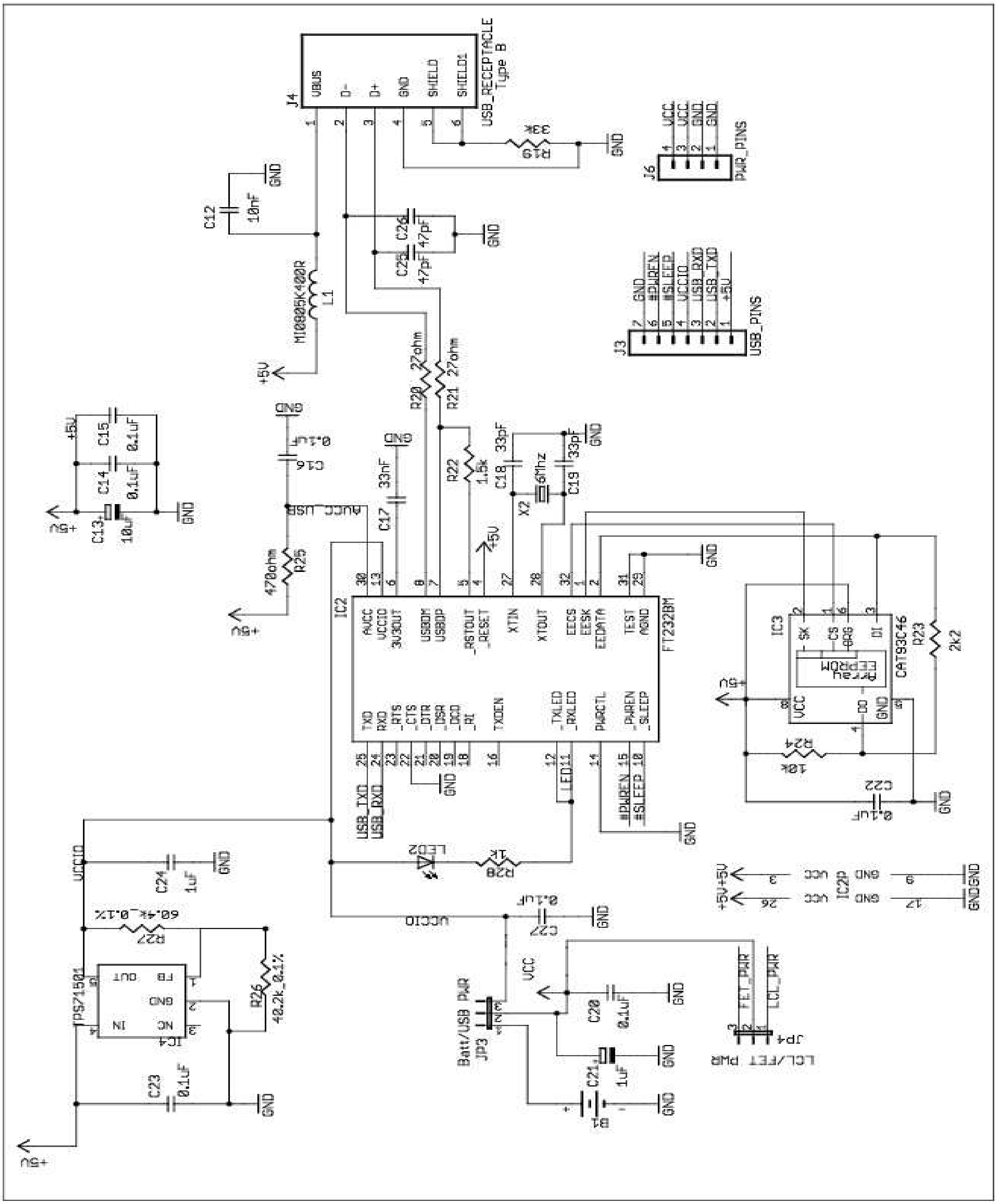

Figure 7. USB Schematic

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