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Lab 14 Report: Optical Heart Rate Sensor

Abstract

Optical heart rate sensors are heart rate measurement devices in which photoplethysmography technique is used. This technique is normally applied by shining an LED through a finger to measure the blood flow. A phototransistor is placed behind that finger to catch the desired wavelength of light, therefore, it can operate in the forward active region, or as a switch. Also, photodiodes are used to modulate the reverse bias current based on the amount of received light. In this report, we apply this methodology to design a basic optical heart rate sensor.

Introduction

This report is meant to design a basic heart rate sensor circuit, which will utilize the use of an LED (IR204) and a phototransistor (PT204-6B), as this pair of equipment can shine infrared light out of the diode and measure the transmitted light. In this report, we plan on tackling this design by divide the parts of the circuit into three different systems: Optical Sensor System, Active Filters, and Analog to Digital System. Eventually, these three parts will be combined to create the optical heart rate sensor.

List of Equipment

- DMM
- Breadboard

- Wires
- LM324N IC Chip
- LM339 IC Chip
- IR204 LED
- PT204-6B Phototransistor
- F3055L NMOS Transistor
- AD2

Theory

As the circuit is divided into three subsystems, each is designed differently, while being applied to different equations to reach the goal of completing a heart rate sensor design.

Optical System:

The main purpose of the optical system is to create an environment where the relationship between an infrared photodiode and an infrared phototransistor can be observed. The components of this system include the IR204 LED, the PT204-6B phototransistor, R_D, and R_E, as the circuit design shown in Figure 1.

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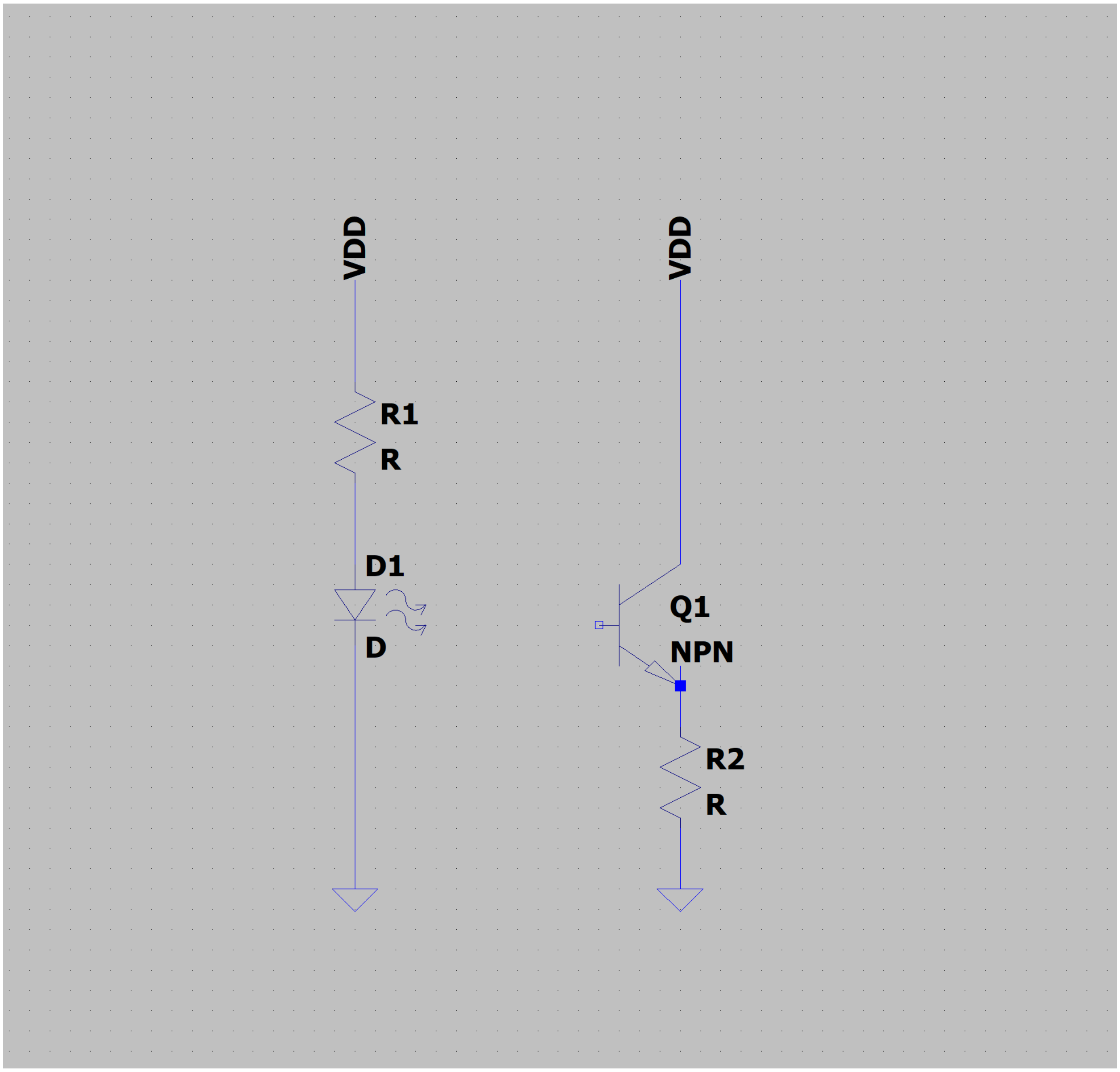

Figure 1. Optical Sensor System Design

Since the LED and the phototransistor are given, the only values that need to be calculated are the resistors R_D and R_E. R_D is obtained by Equation 2 and data from IR204 and PT204-6B datasheets, and while R_E has its own equation for calculation, as depicted in Equation 3 below, we used trials and errors method to find the best possible value for the sensor system.

$$I_D = \frac{V_{CC} - V_D}{R_D}$$

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Equation 1: Current Control through LED Calculation Formula

$$v_{PT} = i_{PT} R_E$$

Equation 2: Phototransistor Current Regulator Calculation Formula

Active Filters System:

As the desired range for this heart rate sensor is from 40 beats per minute (BPM) to 200 BPM, the active filter system needs a high pass filter and a low pass filter. Each filter is comprised of a capacitor and a resistor to adjust its cutoff frequency; and a pair of resistors to adjust its gain. The high pass filter’s input is then connected to the output of the sensor system, while its output node is connected to the input of the low pass filter, as shown in Figure 2.

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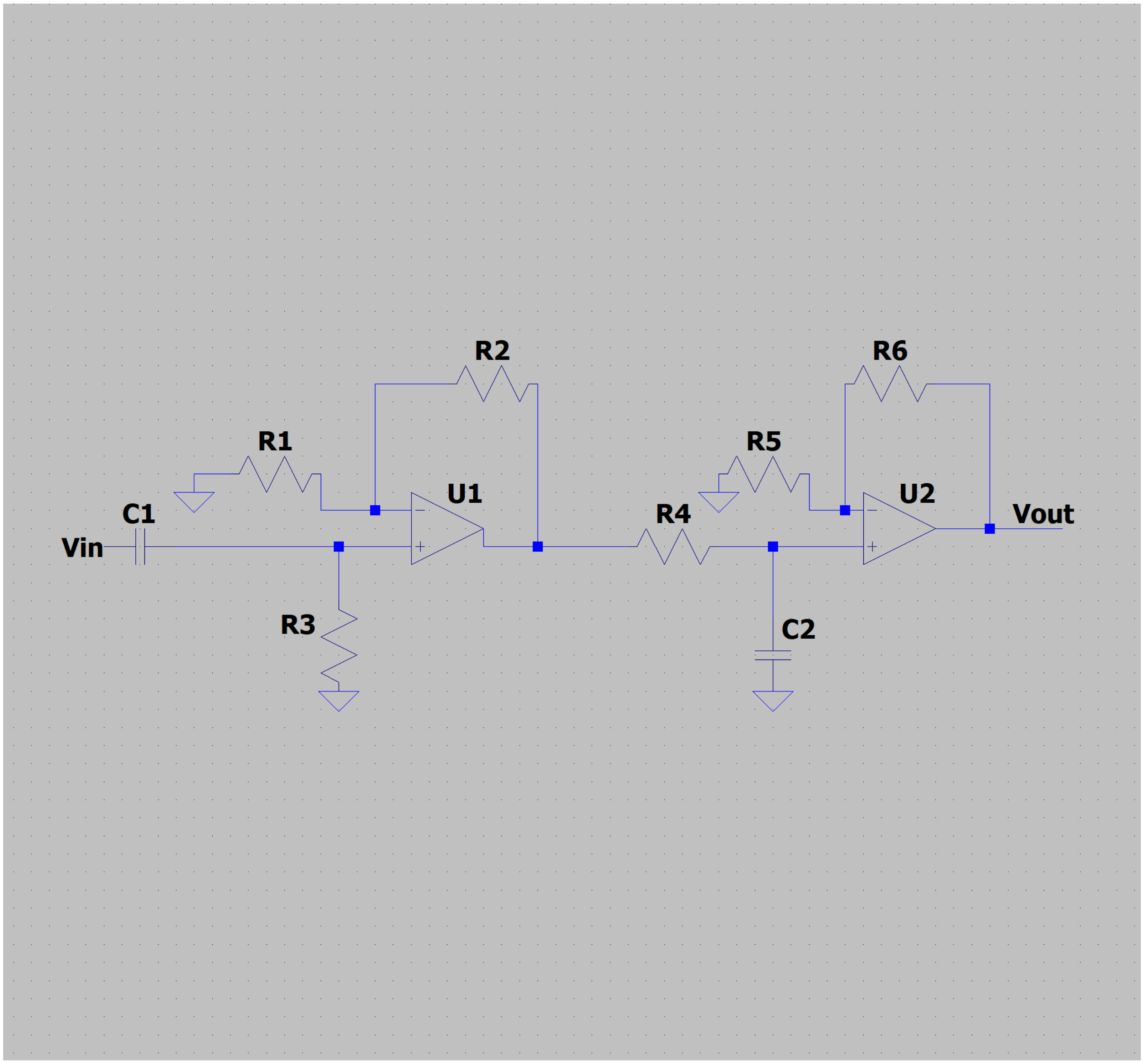

Figure 2. Active Filters System

The aim for this active filters system is to output a gain between 100 and 1000, in which the high pass filter is able to pass slower heart rates, while the low pass filter is able to pass higher heart rate. Equation 3 depicts the calculation for the resistor and capacitor pair for each filter to get their desired cutoff frequency. Equation 4 depicts the calculation for the two resistors pair to get their desired gain.

$$Frequency\ \omega_0 = \frac{1}{2\pi RC}$$

Equation 3: Active Filter's Cutoff Frequency Calculation

$$Gain\ k = 1 + \frac{R_2}{R_1}$$

Equation 4: Gain Calculation for High and Low Pass Filters

Analog to Digital System:

The goal of this subsystem is to turn the output of the active filters system into one bit of signal indicating the detected heartbeat, utilizing an LM339 comparator. That signal will also be used to drive through an LED everytime the heart beat is detected. For this subsystem, we apply a filter with a 2Hz cutoff frequency to feed into the negative terminal of the comparator, while a pair of resistors will be connected to the positive terminal of the LM339 for noise control. The pair of resistor values is calculated as depicted in Equation 5. However, since any reference of V_{hyst} is vague, trials and errors method is used to determine the values of the noise control regulating resistors.

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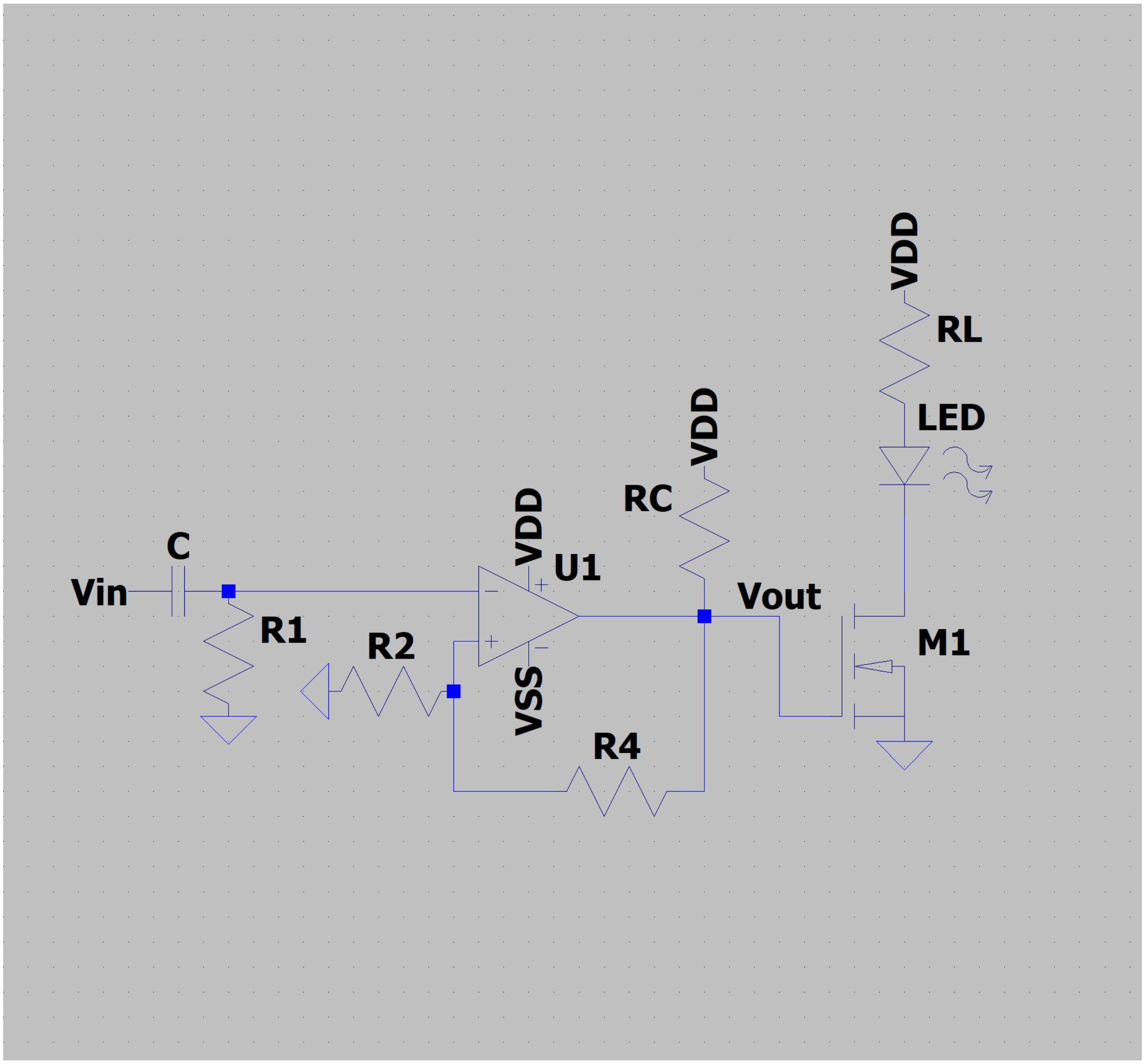

Figure 3. Analog to Digital System Design

$$V_{hyst} = (V_{DD} - V_{SS})\frac{R_1}{R_1+R_2}$$

Equation 5: Noise Control's Resistance Calculation

Percent Error:

Percentage Error is calculated using Equation 6 below for error measurement.

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$$Percent\ Error\ =\ \frac{|Accepted\ Value - Experimental\ Value|}{Accepted\ Value} \times 100\%$$

Equation 6: Percent Error Calculation

Design/Calculations

For the complete design of the optical heart rate sensor, the circuit topologys in Figure 1, 2 and 3 are connected. The full circuit topology is as shown in Figure 4 below.

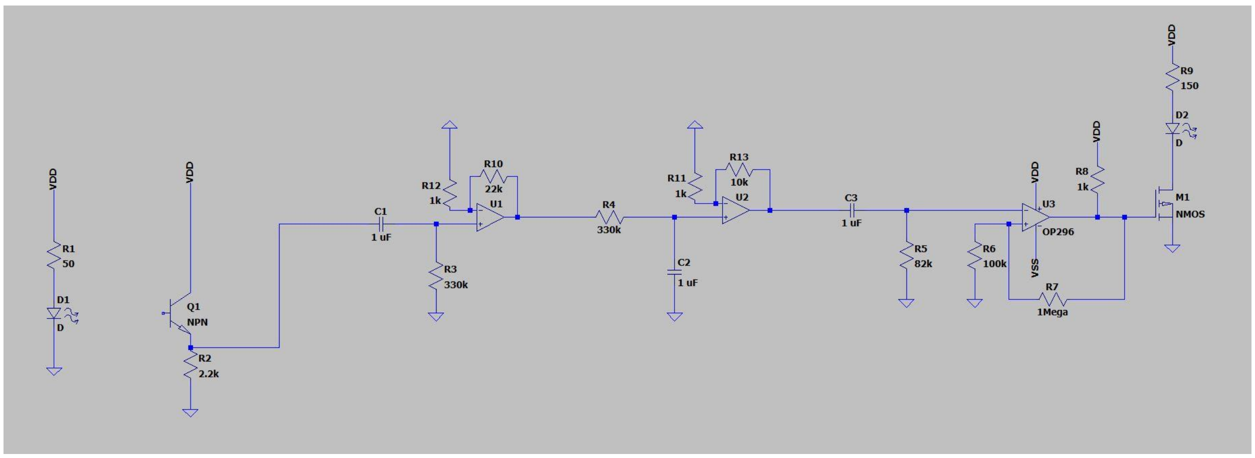

Figure 4. Complete Circuit Schematic

Optical Sensor Calculations:

Using Equation 2 as shown above, and the datasheet of the IR204, we found out that the maximum I_D = 100mA, the minimum V_D = 1.4V. With V_{CC} = 5V, the desired R_D was calculated to be 36Ω. However, in this design we used a compound of resistors with resistance of 38Ω for R_D. For R_E, after using trials and errors method as aforementioned, a compound of resistors with resistance of 5000Ω was used.

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Filter System Calculations:

Using Equation 3 for cutoff frequency calculation, as in the circuit of Figure 2, the equation is applied for the pair of capacitor C_1 and resistor R_3 of the high pass filter; and the pair of capacitor C_2 and resistor R_4 of the low pass filter. Also, the desired cutoff frequency for the high pass filter is lower than 40BPM while that of the low pass filter is 200BPM, therefore, the calculated and chosen values for the capacitors and resistors pairs mentioned are as shown in Table 1 below.

Table 1. Resistor and Capacitor Values to Regulate Cutoff Frequency

Equipment	Resistance ($k\Omega$)	Capacitance (μF)
R_3	330	
R_4	330	
C_1		1
C_2		1

To regulate the gain of the filters, we use the pairs of resistors R_1 and R_2 for the high pass filter's gain, and R_5 and R_6 for the low pass filter. As we want the gain to be between 100 and 1000 and each of their gain should be below 100, in this case we chose it to be around 23 for the high pass filter and 11 for the low pass filter. Apply this to Equation 4, we have table 2 below.

Table 2: Resistor Value to Regulate Active Filters Gains

	R_1	R_2	R_5	R_6
Resistance ($k\Omega$)	1	22	1	10

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Analog to Digital System Calculations:

For this subsystem, we have a first part of a pair of capacitor and resistor going to the negative terminal of the comparator. Applied Equation 3 for this pair of equipment with the desired cutoff frequency of 2Hz, which are resistor R_1 and capacitor C in Figure 3. For resistors R_2 and R_4, though a formula is present as shown in Equation 5, trials and errors method is used to determine their values. For the digital system and indicator part of this subsystem,R_L and R_C, as shown in Figure 3, are predetermined. The values of this subsystem is shown in Table 3.

Table 3: Analog to Digital System's Components Values

Components	Values
R_1	$82k\Omega$
C	$1\mu F$
R_2	$100k\Omega$
R_4	$1M\Omega$
R_C	$1k\Omega$
R_L	150Ω

Results

Optical Sensor:

For this first part of the circuit, after connecting a 5V supply input to the sensor circuit, we captured the pulsed LED behavior of the system as shown in Figure 5 below. As observation. the pulsed LED behavior is measured at the PT204-6B phototransistor receiver's emitter node. This behaviour has turned out to be as expected for the heart rate pulses.

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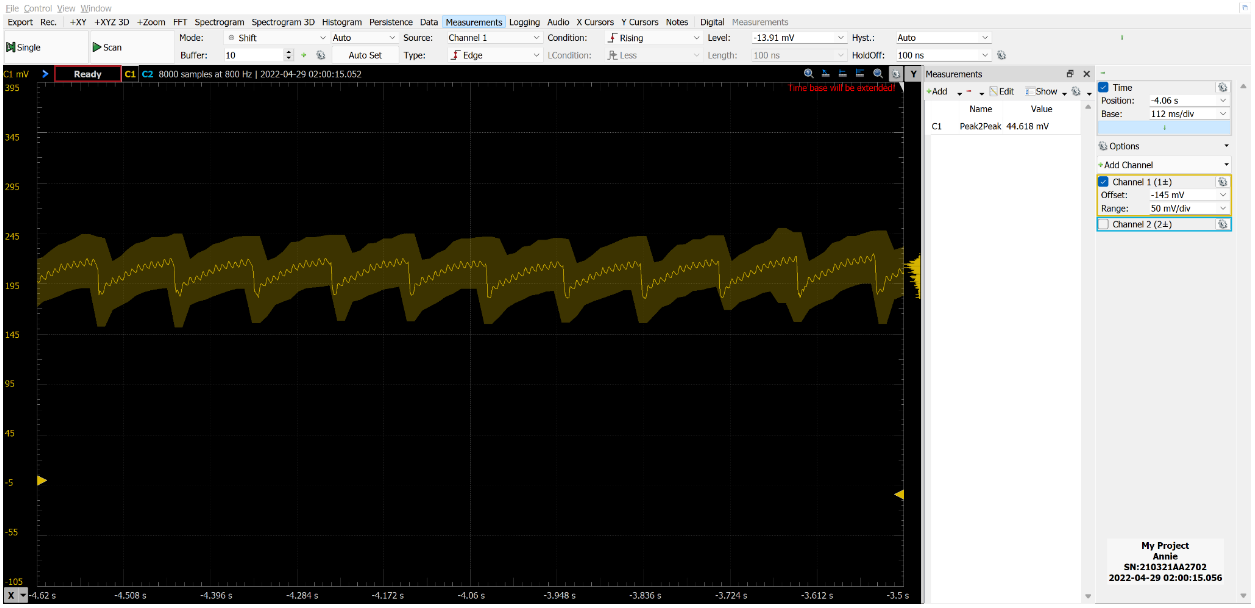

Figure 5. Optical Sensor System Output

Active Filters System:

High Pass Filter:

As observed from Figure 6, the cutoff frequency, the frequency at -3dB point, is shown to be 0.69946 Hz. The desired cutoff frequency was set to be around 40BPM, or 0.67Hz, using Equation 6, the calculated percent error is measured to be 4.2118%.

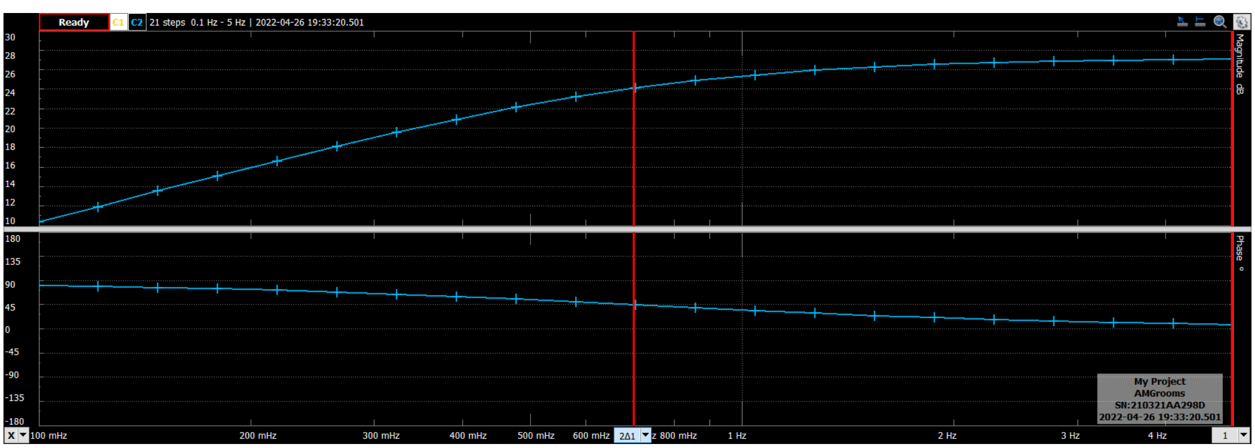

Figure 6. High Pass Filter Frequency Response

As observed from Figure 7, the gain at -3dB point is shown to be 22.5. The desired gain was set to be around 23, using Equation 6, the calculated percent error is measured to be 2.1739%.

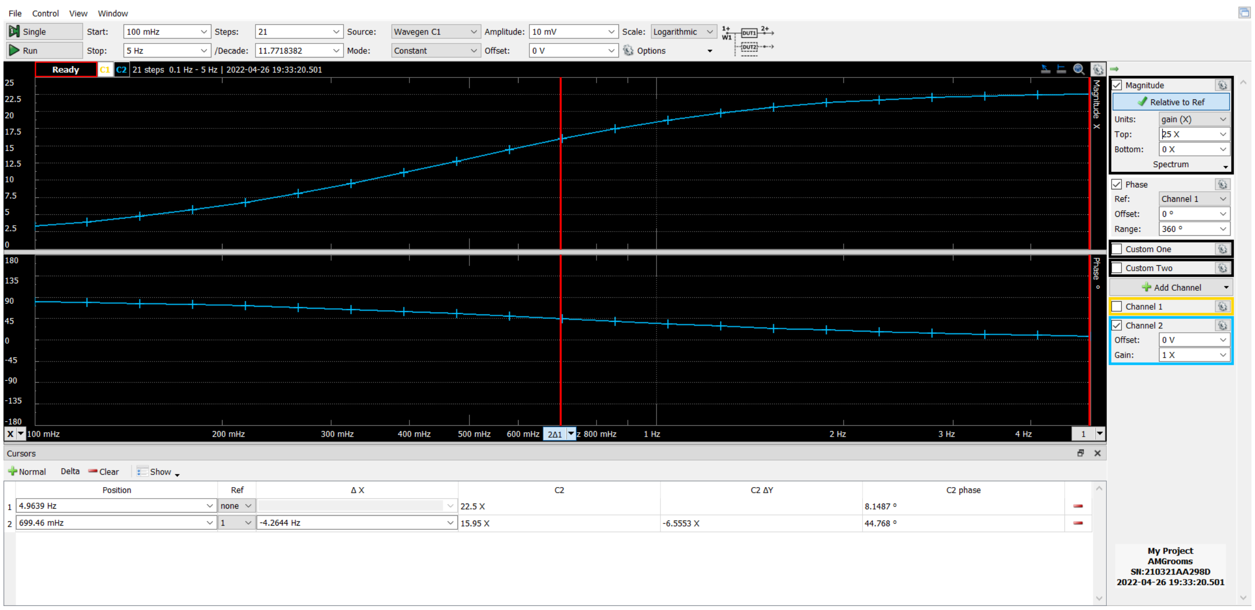

Figure 7. High Pass Filter Gain Response

Low Pass Filter:

As observed from Figure 8, the cutoff frequency, the frequency at -3dB point, is shown to be 3.8336 Hz. The desired cutoff frequency was set to be around 200BPM, or 3.3Hz, using Equation 6, the calculated percent error is measured to be 16.1697%.

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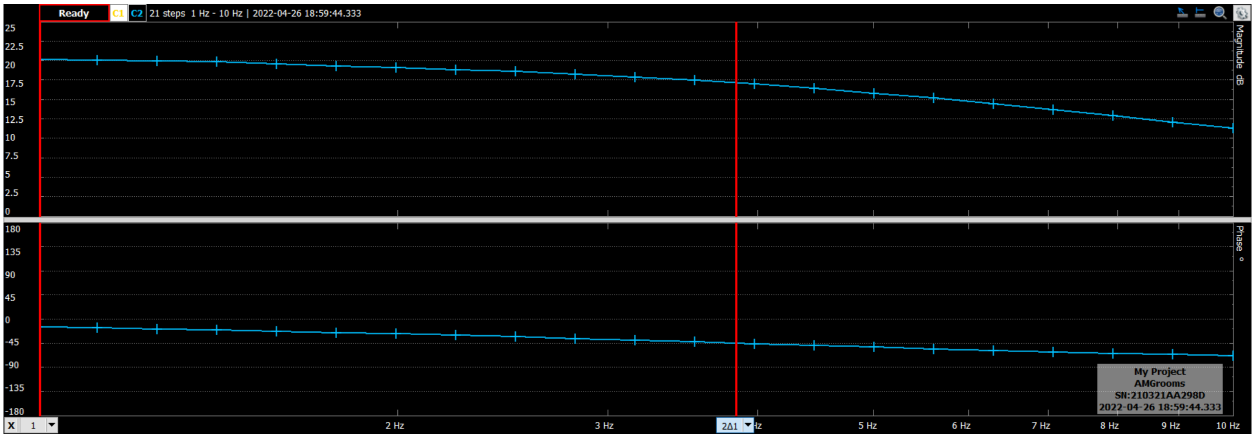

Figure 8. Low Pass Filter Frequency Response

As observed from Figure 9, the gain at -3dB point is shown to be 10.13. The desired gain was set to be around 11, using Equation 6, the calculated percent error is measured to be 7.9091%.

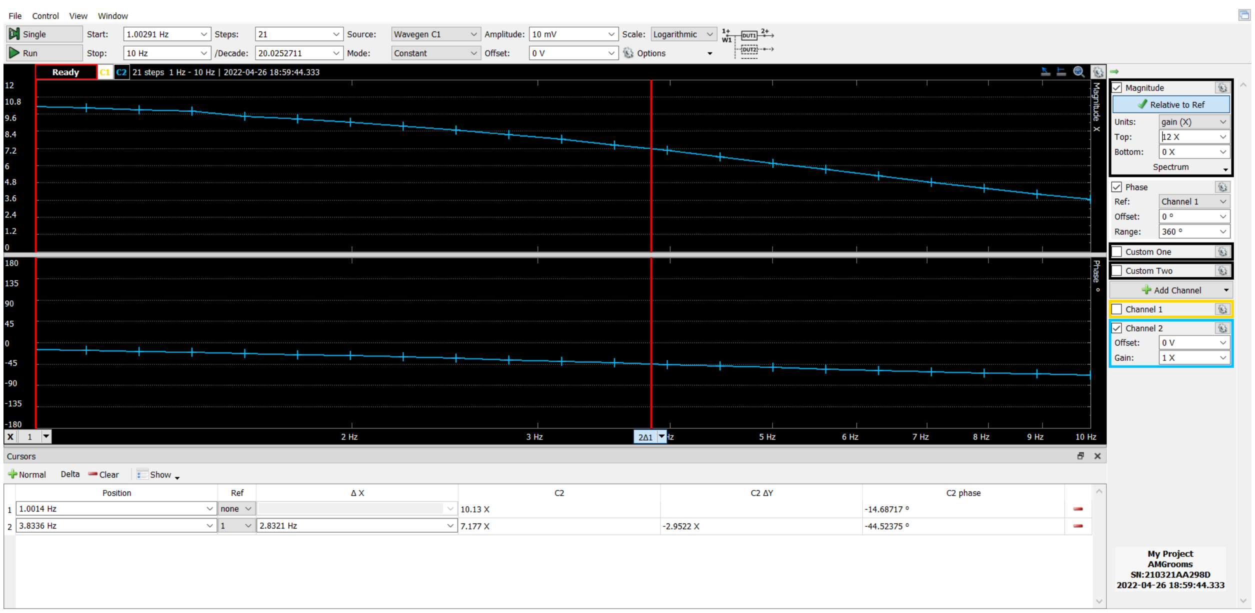

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Figure 9. Low Pass gain frequency response with -3dB cutoff

Combined Filter Chain:

As observed from Figure 10, the frequency response graph curves upward at the -3dB point of the high pass filter, and it curves back downward at the -3dB point of the low pass filter.

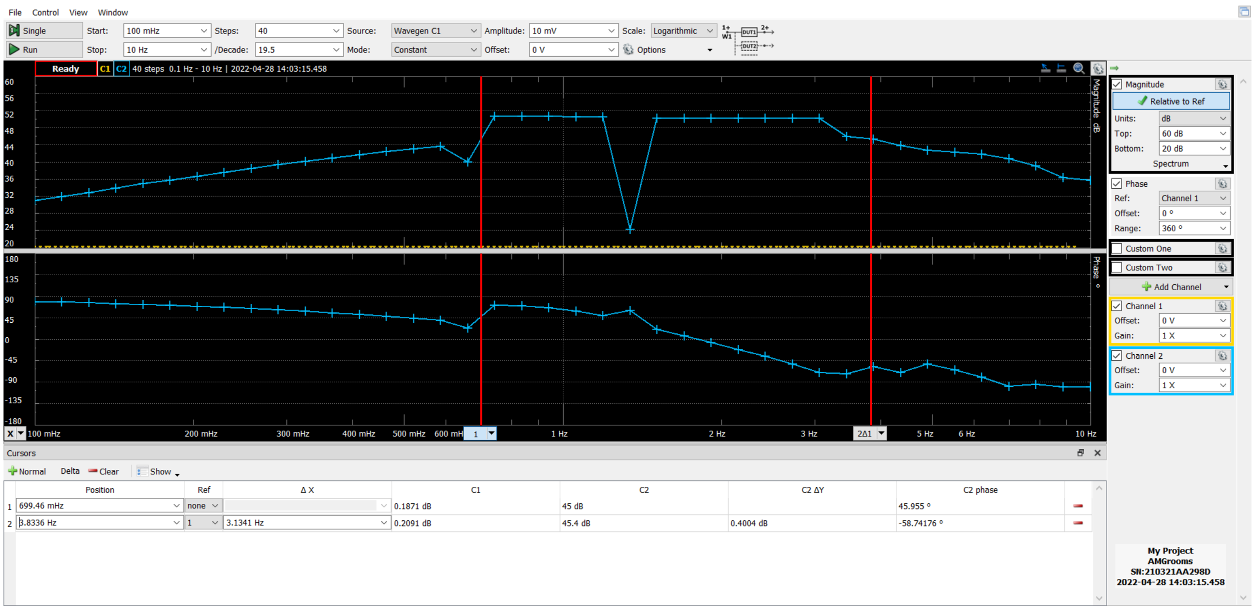

Figure 10. Active Filters System Frequency Response

As observed from Figure 11, the combined gain of the full active filters system is measured to be as high as 324.2. The desired combined gain is set to be at around 253, using Equation 6, the percent error is calculated to be 28.1423%.

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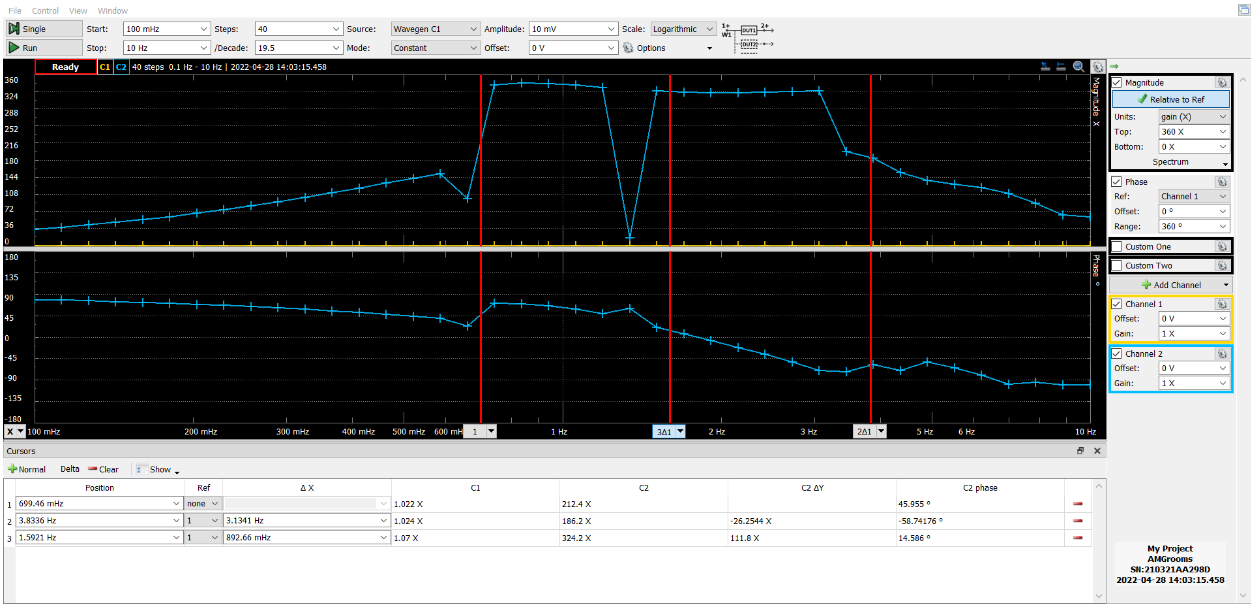

Figure 11. Active Filters System Gain Frequency Response

Analog to Digital Converter:

The digital waveform output for the analog to digital converter system is as shown in Figure 12. This is the expected output by the LM339 comparator as seen in Channel 1 (yellow waveform), as a digital square wave.

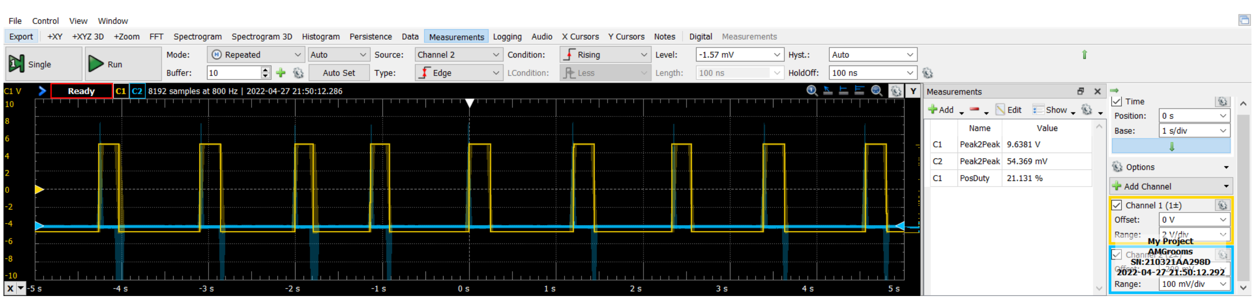

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Figure 12. Analog to Digital System Output

Functionality Plots:

As seen from Figure 13, the outputs of the optical sensor system (Channel 2 - Blue waveform) and that of the full circuit (Channel 1 - Yellow waveform) are shown. This graph is generated as the circuit is functioning, measuring a person's blood flow/heart rate through their fingertip put in between the optical sensor system.

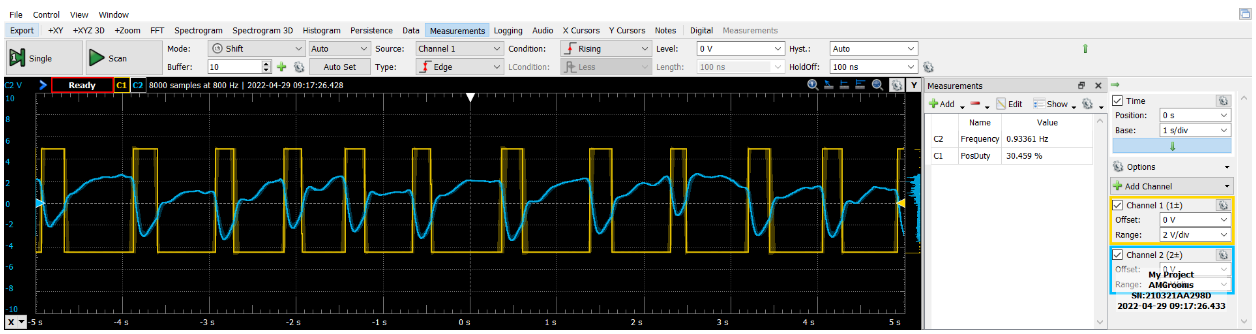

Figure 13. Full Circuit Overlapping Input and Output

Conclusion

This report has successfully achieved its purpose of constructing a basic optical heart rate sensor. There are errors that was seen throughout the report on each of the subsystem, which are due to slight chip malfunctioning or human/calculation error when choosing suitable components for the project. Overall, this project has managed to create a functional, basic optical heart rate sensor.