Richard Li
Partner: Bhaskar Patke

ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

Abstract:

The purpose of this experiment was to create a circuit that can sense the heart rate of a human being (40 bpm to 200 bpm). This circuit will convert the input of an optical sensor into a binary signal. This circuit was created using an IR transmitter and receiver as the sensor, active first order filters to create a bandpass frequency range, a comparator to act as an ADC, and a final led mosfet circuit as a visual display. All parameters were met during this project.

Equipment:

List of components/equipment: There should be a subsection including the components and equipment used in the experiment.

- AD2
- IR transmitter (IR204) and Receiver (PT204-6B)
- Components:
    - MOSFETS: 2 FRD3055 NMOS transistors
    - Capacitor: 3 10nF capacitors
    - LED: red led
    - Multiple resistors

Richard Li
Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

1. Introduction:

Heart rate sensors are widely used as a heuristic measurement of one's current bodily condition. For example, they are often used in exercise equipment. Heart rate monitors are also used in hospitals to keep track of a patient's health. The objective of this lab is to create a simple and accurate heart-rate sensor using IR sensors and filters.

1.1 Optical sensor:

The optical sensor uses an IR LED and phototransistor pair to detect changes in blood flow and convert this into an electric analog signal. The IR led shines infrared light through the finger to the phototransistor, which allows the phototransistor to measure the heart rate.

1.2 High pass filter:

The high pass filter allows only heart rates over 40 BPM to pass, cleaning the signal.

1.3 Low Pass filter:

The low pass filter allows only heart rates below 200 BPM to pass, cleaning the signal.

1.4 Analog to Digital Circuit:

The analog to digital circuit converts the filtered output analog signal into a binary signal that indicates when a heart beat occurs.

2. Theory:

2.1 Optical sensor:

The optical sensor is constructed using the key components of a Infrared LED and a phototransistor. Heart rate is measured by placing the finger between the LED and the phototransistor. Since changes in blood flow cause changes in the infrared light penetration of the blood, placing a finger between the LED and the phototransistor allows for the phototransistor to detect heart beats by sensing changes in the infrared light detected.

To maximize efficiency and accuracy, the infrared LED (transmitter) and phototransistor (receiver) should be operating at the same wavelength. The IR LED should also be operating at maximum capacity: the current through the LED should be maximized.

The current through the LED can be calculated as follows, in a simple LED resistor circuit:

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

Note that the resistor in this circuit must also dissipate less power than this resistor's maximum rated power:

$$P = \frac{V^2}{R}$$

Similarly, a resistor in series with the phototransistor is chosen such that it maximizes DC offset.

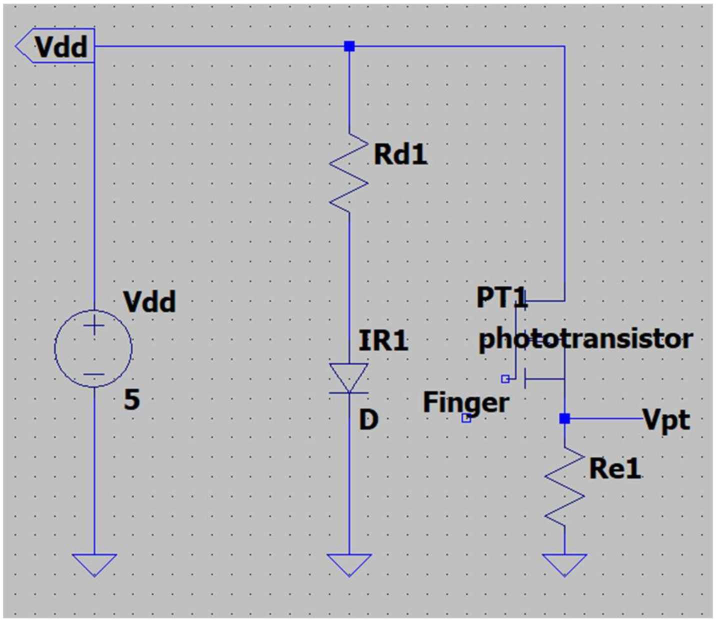

Figure 1: Optical sensor circuit topology

2.2 High pass Filter:

A high pass filter is used to filter out signals that are too low to be a plausible heart rate, and thus must be noise. Thus, only frequencies above a certain BPM are registered. For the high pass filter, the minimum BPM serves as the cutoff frequency.

The cutoff frequency and angular cutoff frequency can be calculated as follows:

$$f = \left(\frac{BPM}{60}\right) hz$$

$$w_0 = 2\pi f$$

A noninverting first order highpass filter can be used for as the circuit:

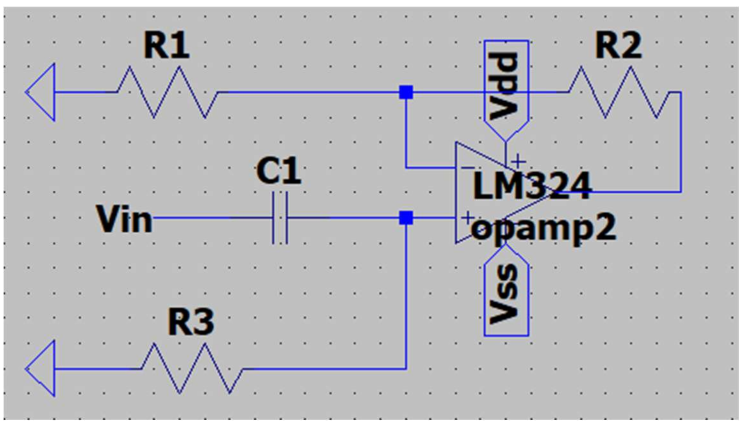

Figure 2: circuit topology of first order highpass filter

This circuit topology implies:

Gain:

$$Av = 1 + \frac{R2}{R1}$$

Cutoff frequency:

$$\frac{1}{R3 * C1}$$

Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

2.3 Low pass filter:

Similar to the high pass filter, the low pass filter filters out signals with a frequency too high to plausibly be a heart rate and thus must be noise.

The angular cutoff frequency for the low pass filter can be calculated as follows:

$$w_0 = 2\pi(\frac{BPM}{60})$$

A noninverting first order low pass filter can be used for this circuit:

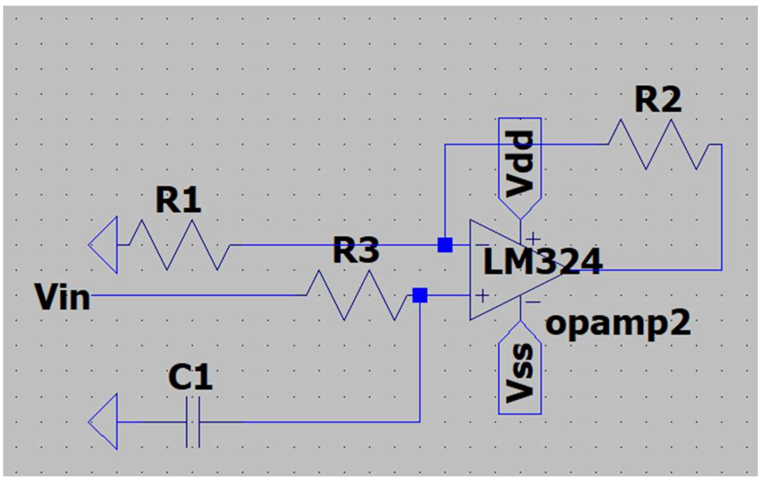

Figure 3: circuit topology of first order lowpass filter

The relevant quantities can be calculated using the same equations as the high pass filter:

Gain:

$$Av = 1 + \frac{R2}{R1}$$

Cutoff frequency:

$$\frac{1}{R3 * C1}$$

2.4 Analog to Digital:

The analog to digital conversion circuit is used to convert the final filtered circuit into a binary signal with active low output (0V indicates a heart beat detected). This circuit is implemented using a comparator designed with hysteresis to reduce noise.

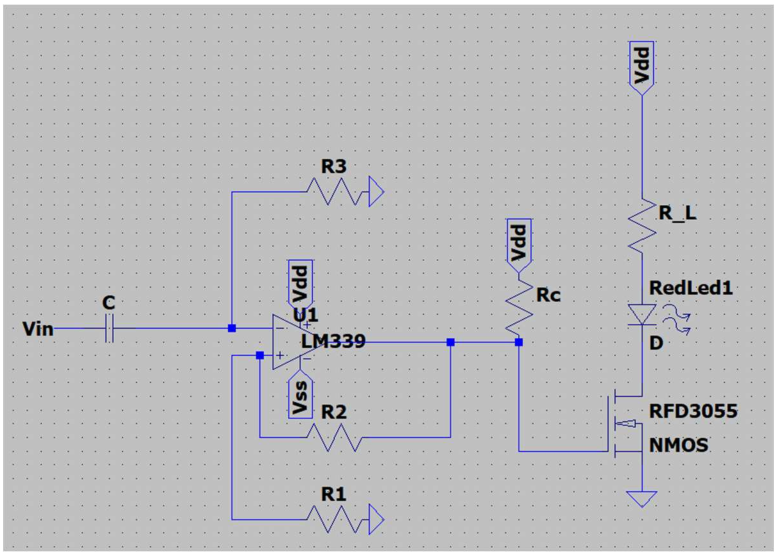

Figure 4: Circuit topology of comparator with hysteresis with low-active output led.

Hysteresis of the comparator is the difference between the cutoffs of the comparator that cause a rising edge and falling edge in the signal. It should be larger than the noise in the signal to avoid noise from influencing the final digital output, and also be smaller than the Vpp of the heartbeat signal in order to trigger a rising or falling edge correctly. It depends on R1 and R2, which are typically chosen to be more than 100k-ohms to maintain the high input impedance of the comparator.

$$V_{hys} = (V_{dd} - V_{ss}) * (\frac{R1}{R1 + R2})$$

Additionally, Vhyst should be relatively small compared to the source voltages:

$$\frac{V_{hyst}}{V_{dd} - V_{ss}} < 0.1$$

The cutoff frequency of this circuit is determined by R3 and C:

$$w_0 = \frac{1}{R_3 * C}$$

For the final LED display, Rl should be chosen to maximize current through the LED in the same manner as was done for the infrared LED in the section 2.1 optical sensor.

3. Design and Calculations:

3.1 Optical sensor:

The chosen infrared transmitter LED was IR204 and the chosen receiver was PT204-6B.

For the transmitter, the maximum current for the minimum voltage drop is 0.1 A continuous forward current. The forward drop is 1.4 V. The supply voltage is 5V. Thus:

$$R_d = \frac{V_{cc} - V_d}{I_d}$$

$$R_d = \frac{5 - 1.4}{0.1} = 36\ \Omega$$

However, this is above the maximum power dissipation of the resistor at 0.25W:

$$P = I^2R = (0.1)^2(36) = 0.36\ W > 0.25\ W$$

Thus, to dissipate power, more resistors can be used, to split the power consumed. The closest values are 68 ohm and 82 ohm. Thus:

$$R_d = 68\,||\,82 = 37.17\ ohm$$

$$I_d = \frac{5 - 1.4}{37.17} = 0.096\ A$$

$$P_{R6} = \frac{(5 - 1.4)^2}{68} = 0.191\ W$$

$$P_{R8} = \frac{(5 - 1.4)^2}{82} = 0.158\ W$$

Thus, all power consumed is less than 0.25W, and the power through the diode is maximized because the current is maximized, as 0.096 A is very close to the max 0.1A.

Re was experimentally found using a potentiometer ranging from 0 ohm to 10k ohm, adjusted until the AC signal was ranging from 10mVpp to 100 mVpp.

Richard Li
Partner: Bhaskar Patke

ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

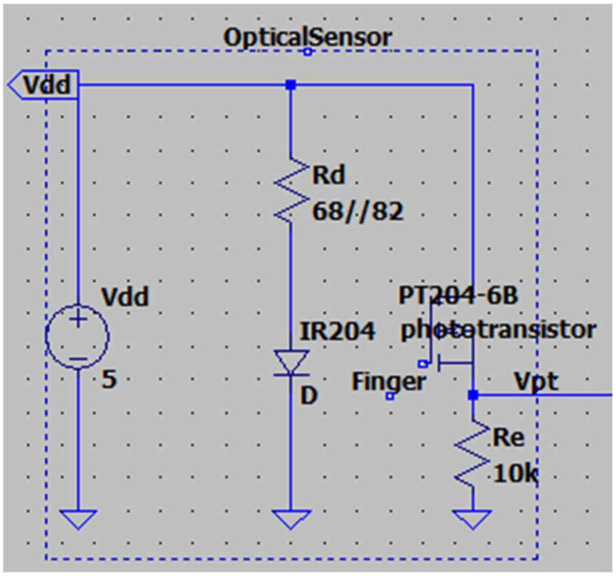

Figure 5: optical sensor circuit with values.

3.2 High pass Filter:

Specifications: The high pass filter should allow heart beat rates of 40 BPM or higher and have a gain between 10 and 100. R1 and R3 should remain similar to ensure there is no offset. The capacitance is assigned 10-microF for convenience.

$$w_0 = 2\pi\left(BPM * \frac{1\text{ min}}{60\text{sec}}\right) = 2\,\pi\left(40 * \frac{1}{60}\right) = 2 * \pi\frac{40}{60} = \frac{4}{3}\pi$$

$$w_0 = \frac{1}{R_3C} = \frac{1}{R_3(10u)} = \frac{4}{3}\pi$$

$$R_3 = 23873.24\Omega$$

This resistor is not available in lab and must be rounded. Since the high pass filter will meet specifications if the cut off frequency is the same or less than expected, the resistor should round up. Thus, R3 rounds to 33k-ohm.

The cut off frequency is found as follows:

$$w_0 = \frac{1}{R_3C} = \frac{1}{(33k)(10u)} = 3.03\ radians/s$$

$$f = \frac{1}{2\pi} * w_0 = \frac{1}{2\pi} * 3.03 = 0.482\ Hz$$

Thus, the cutoff frequency is theoretically 0.482 Hz. For simplicity, the gain of this circuit was set to 11. R1 was set to 33k-ohm to be as similar as possible to R3, which is 33k-ohm.

$$A_v = 1 + \frac{R2}{R1} = 1 + \frac{R2}{33k}$$

$$A_v = 1 + \frac{330k}{33k} = 11$$

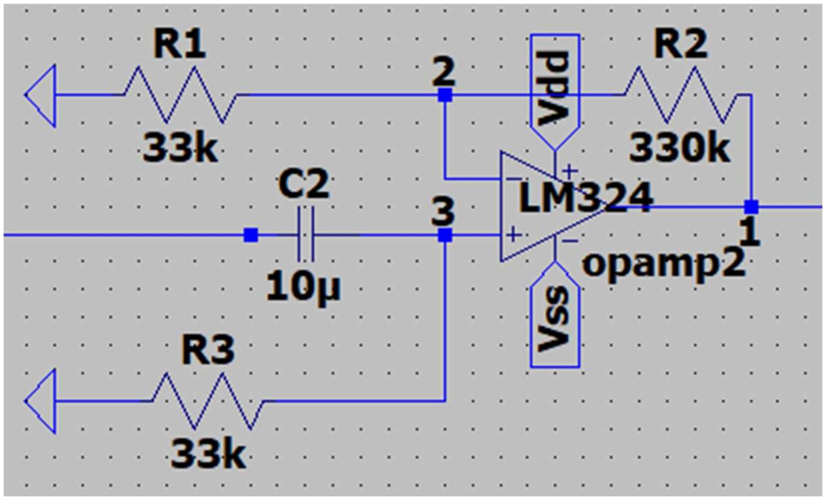

Figure 6: non inverting high pass filter circuit with values.

3.3 Low pass Filter:

Similar to the high pass filter, the low pass filter is designed such that the heart rate should, instead, allow signals 200 BPM and below to pass, the gain should be between 10 and 100, R1 and R3 should be of similar magnitude, and for convenience, the capacitance should be set to 1uF.

This implies:

$$w_0 = (200) * \frac{\pi}{30} = \frac{20}{3}\pi$$

$$w_0 = \frac{1}{R_3 C} = \frac{1}{R_3 * 1u} = \frac{20}{3}\pi$$

$$R_3 = 47746\ \Omega$$

Since this resistor value is hard to find, it must be rounded to one that is. The low pass filer should have a cutoff above 200 BPM, so R3 must be rounded down. Thus, R3 = 47k-ohm. Thus:

$$w_0 = \frac{1}{R_3 C} = \frac{1}{47k * 1u} = 21.276\frac{radians}{s}$$

$$f = \frac{1}{2\pi} * w_0 = 3.386\ Hz$$

The expected frequency is 3.701 Hz. To match R3, R1 was set to 47k-ohm. For simplicity, gain was set to 11. Thus, R2 = 470k-ohm.

$$A_v = 1 + \frac{R2}{R1} \rightarrow 11 = 1 + \frac{470k}{47k}$$

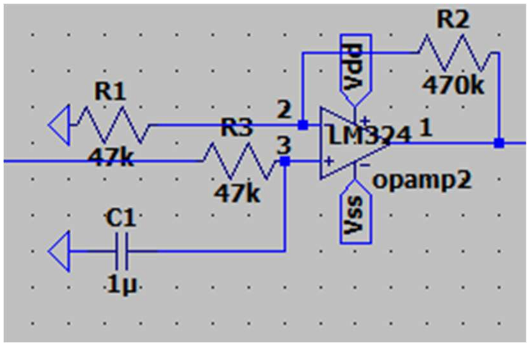

Figure 7: noninverting low pass filter with values

3.4 Analog to digital circuit:

Vhyst was selected to be 0.91. Thus:

$$V_{hyst} = (V_{dd} - V_{ss}) * \left(\frac{R1}{R1 + R2}\right) = \big(5 - (-5)\big) * \left(\frac{150k}{150k + 1560k}\right) = 0.91$$

Also:

$$\frac{V_{hyst}}{V_{dd} - V_{ss}} = \frac{0.91}{5 - (-5)} = 0.091 < 0.1$$

Thus, R1 = 150k, R2 = 1M + 560k,

The cutoff frequency of this circuit is determined by R3 and C and should be 2Hz or lower. A capacitor value of 1uF was selected. Thus:

$$w_0 = \frac{1}{R_3 * C} \to 2 * 2\pi = \frac{1}{R3 * 1u} \to R3 = 80kohm$$

To maintain a cutoff frequency of 2Hz or lower, R3 was rounded up to 82k-ohm.

Rl, the resistor of the Led, was experimentally set to 150ohm.

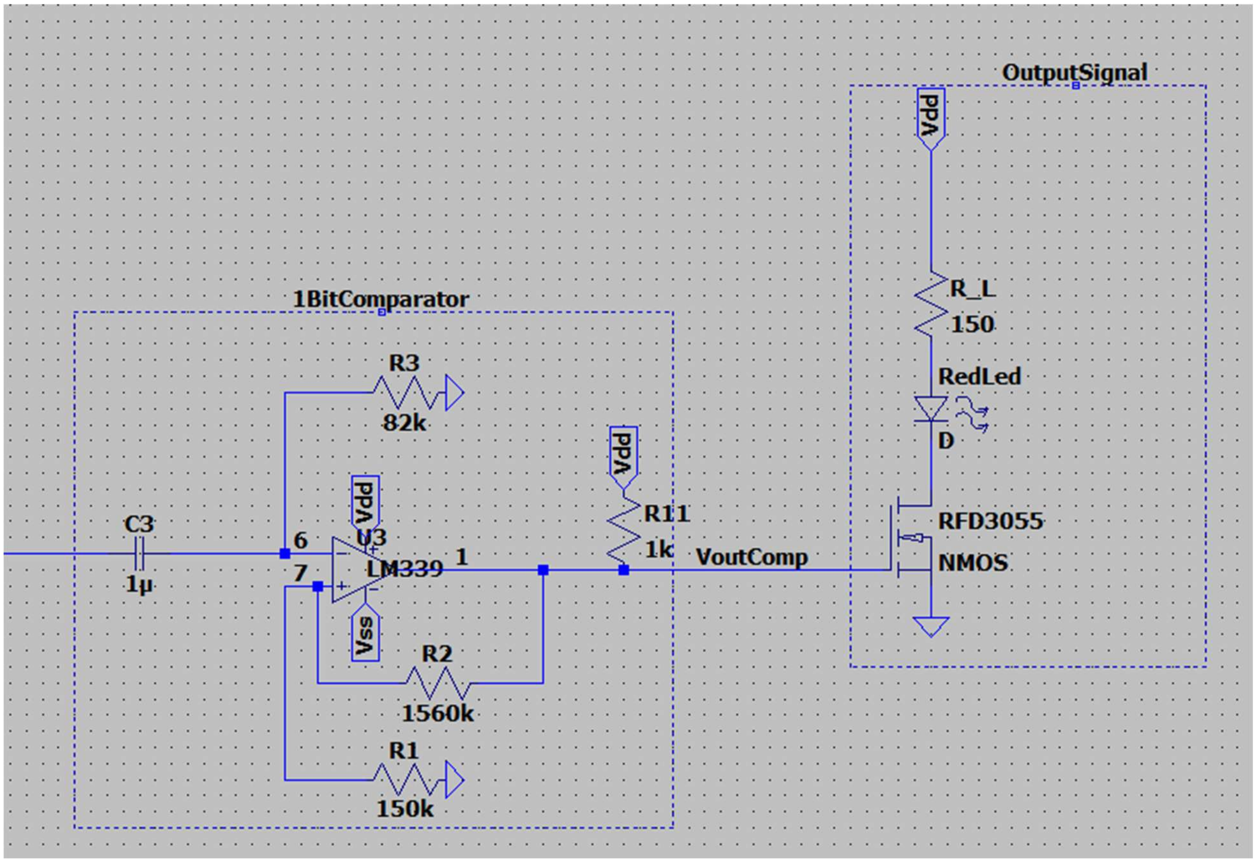

Figure 8: Final comparator circuit with LED indicator with values.

3.5 Integrated circuit:

The full circuit is constructed with the following circuits in series, in order: optical sensor, high pass filter, low pass filter, comparator, LED display indicator.

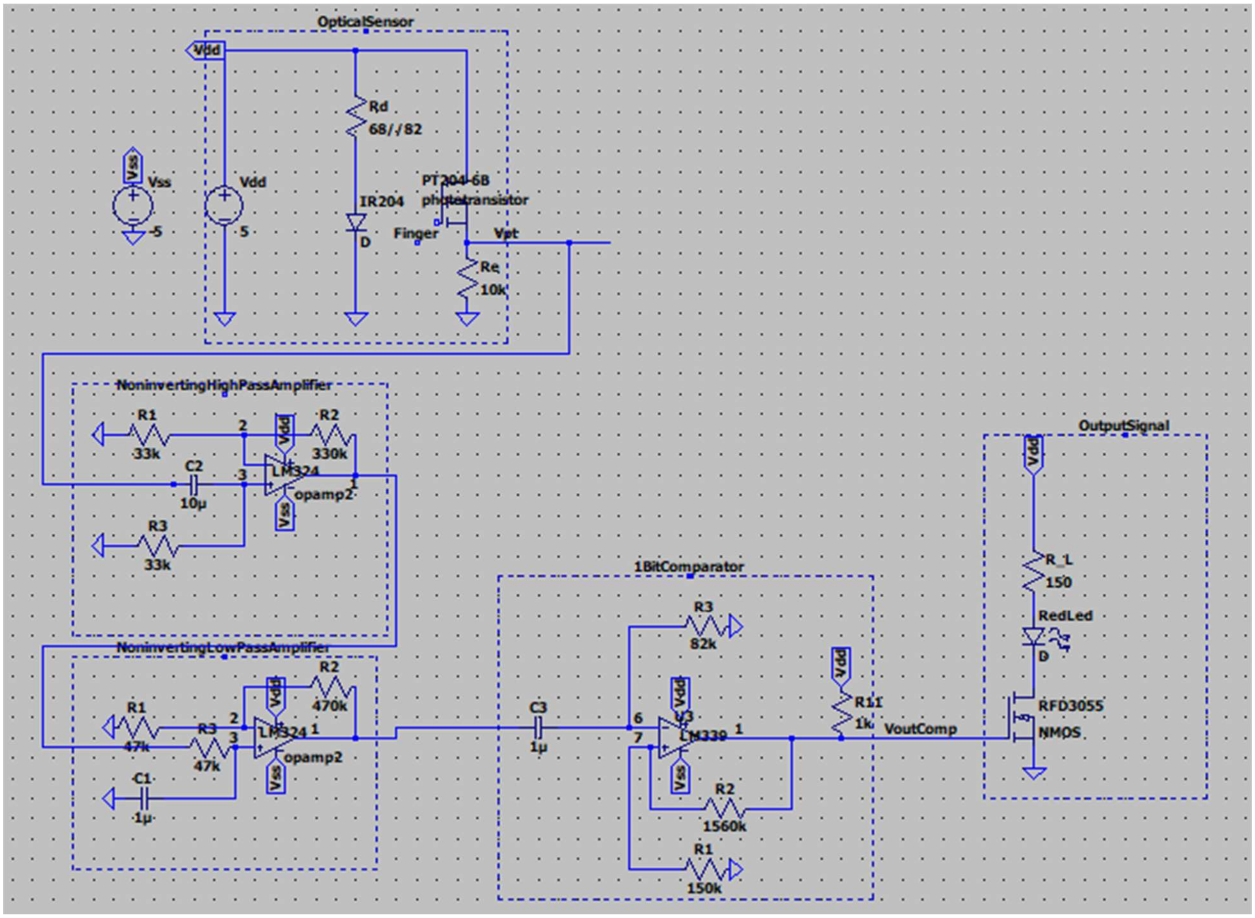

Figure 9: Final heart rate sensor schematic

Note how the high pass filter comes before the low pass filter. This order is important because the input capacitor of the high pass filter removes DC offset from the optical sensor, which is critical to the functionality of the circuit. The low pass filter does not have this.

Richard Li
Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

4. Results

Each circuit-module will be discussed individually, in order of current flow, and then the final circuit with integrated modules will be discussed.

4.1 Optical sensor:

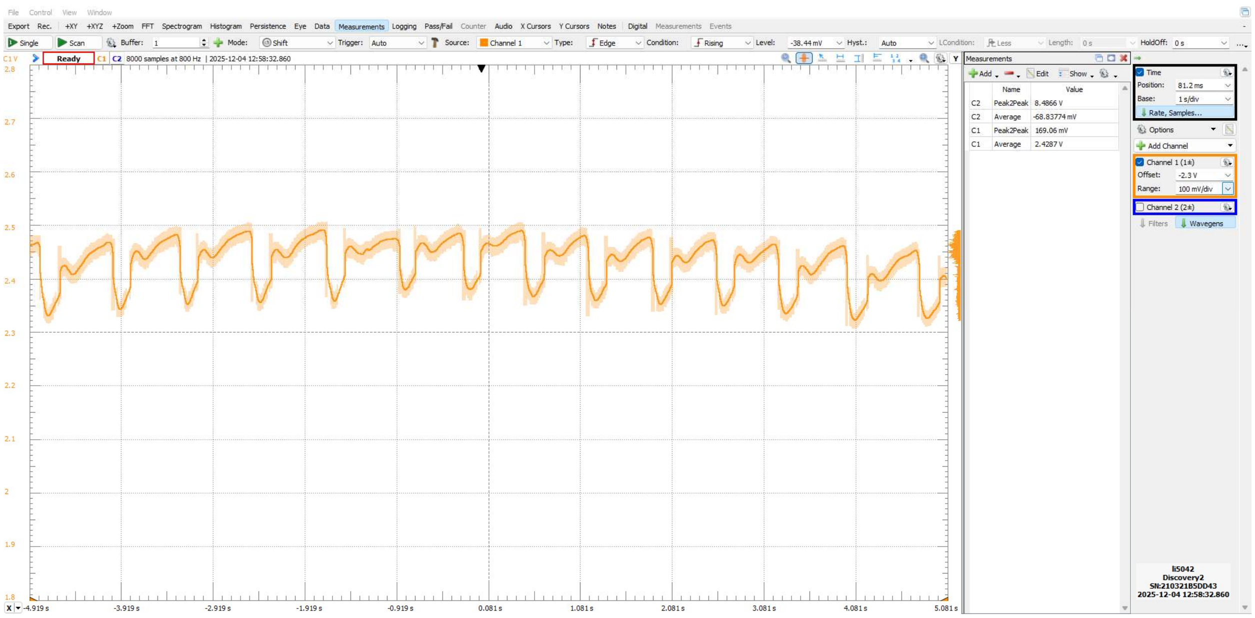

Figure 10: Optical sensor output

The optical sensor works as expected: putting a finger between the IR transmitter and IR receiver allows for pulses of blood to be detected, and thus heartrate to be detected.

The chosen resistance for Re, the resistor in series with the IR receiver, was experimentally found to be 4.7k-ohm.

It was important to make sure that not only were the sensors pointing at each other, but also that the finger blocked all paths from the sensor to the receiver, forcing the infrared light to pass through the finger.

The peak to peak voltage of the received signal as 169 mV with an average of 2.4 V, which is within the requirements of: 10-100mVpp with any DC offset.

4.2 High pass Filter:

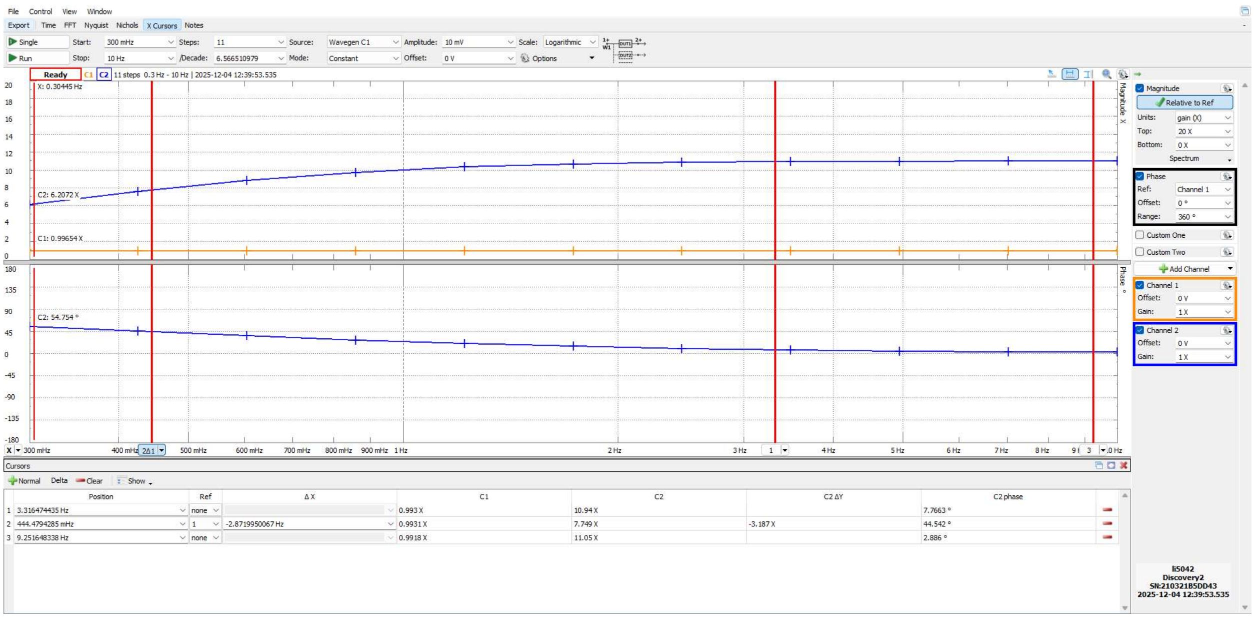

Figure 11: FRA of high pass filter module.

The high pass filter worked as expected: the filter allows high frequencies to pass (gain of 11 times, as calculated) with a cutoff frequency of 444 mHz. The expected cutoff frequency is 0.482 Hz.

Percent error: 7.9%

The low percent error indicates that the high pass filter works as expected.

Richard Li
Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

4.3 Low pass filter:

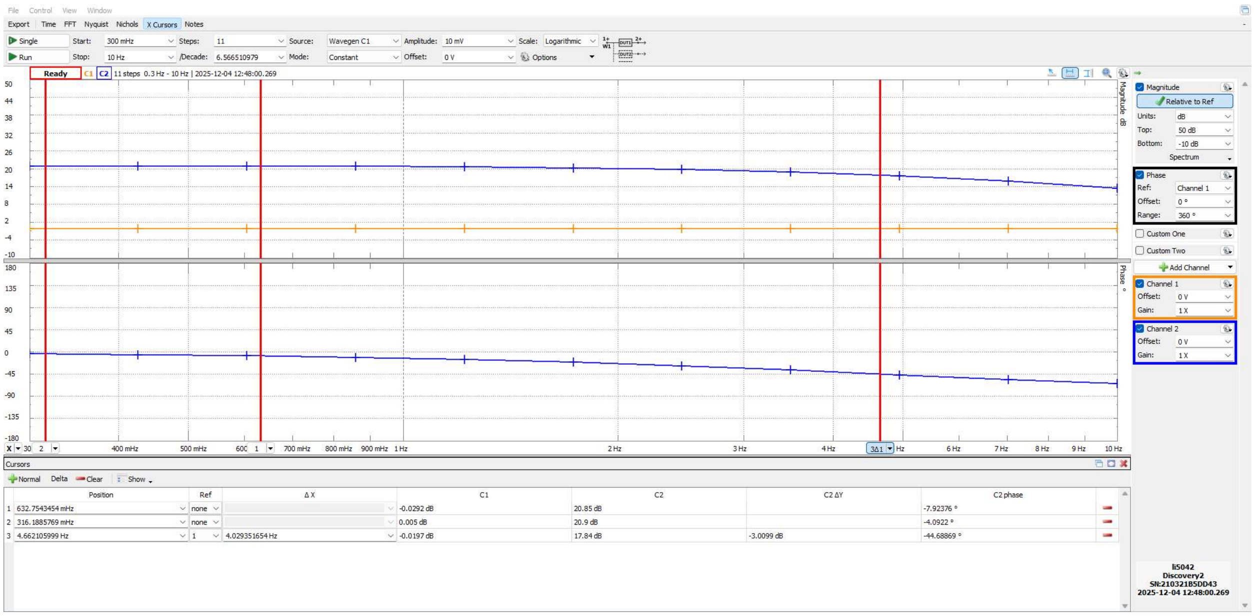

Figure 12: FRA of low pass filter.

The low pass filter works as expected, by allowing low frequencies to pass while cutting off high frequencies. The passband gain is 20.9 dB (= 11.1 times increase), with a -3 cutoff point is 4.66 Hz. The expected cutoff frequency was 3.386.

Percent error: 37.6%.

The high percent error is likely due to the inaccurate capacitor (1u), of which small variations can greatly change the filter cutoffs. However, since the cutoff is still greater than the criteria, it is still acceptable.

4.4 Band pass Filter :

The high pass and low pass filters were put in series to create a passband filter.

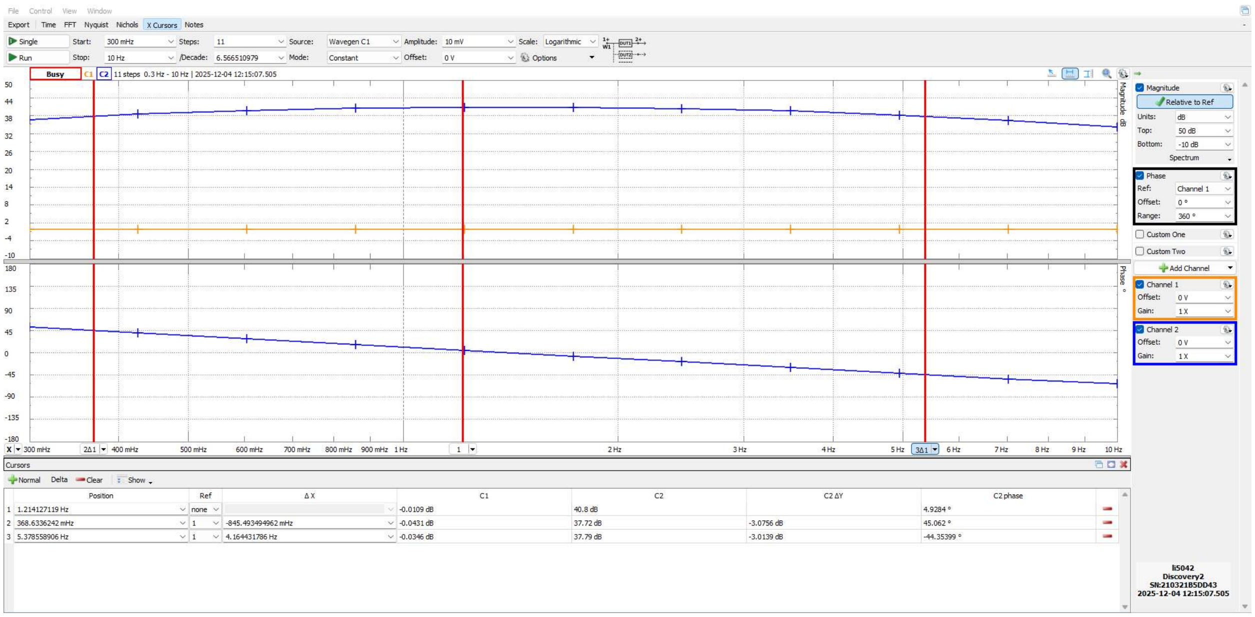

Figure 13: FRA of bandpass filter

The bandpass filter had a passband gain of 40.8 dB with a low cutoff of 0.368 Hz and a high cutoff of 5.37 Hz. This is larger than the required range of 0.482 Hz to 3.33 Hz, so it is acceptable.

While this will allow more noise into the circuit, this was experimentally found to not be a problem with the functionality of the circuit.

Richard Li

Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

4.5 Analog to Digital:

The analog to digital module was tested by inputting a signal of expected parameters into the comparator (analog to digital) module.

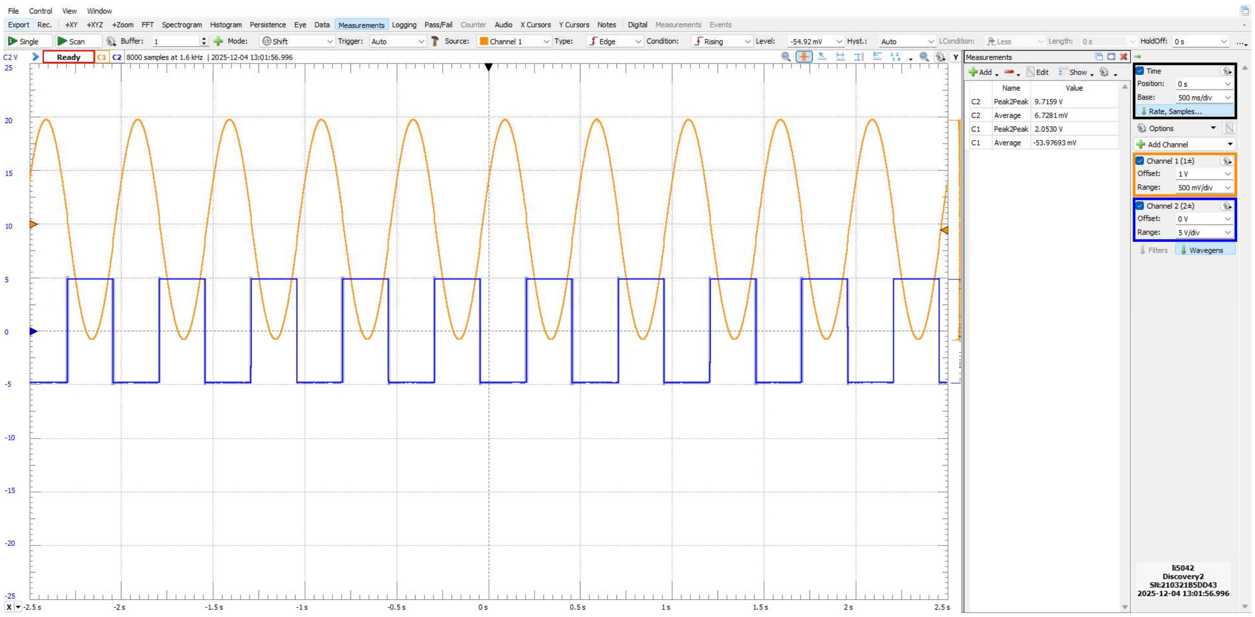

Figure 14: Comparator module with 2Hz 2Vpp input

The output is a clear inversion of the input with hysteresis (offset cutoffs), and has a Vpp of 9.7 V with an average of about 0V. This indicates that the output signal ranges from -5 to 5V with (approximately) 0 DC offset, meaning it works as expected.

Percent error of Vpp (expected: 10V): 3%

Richard Li
Partner: Bhaskar Patke
ECE 20008-005
Lab 14- Optical Heart Rate Sensor
11/20/2025

4.6 Final Implementation:

The integrated circuit means connecting all modules together following the integrated circuit schematic.

Testing with a finger yields:

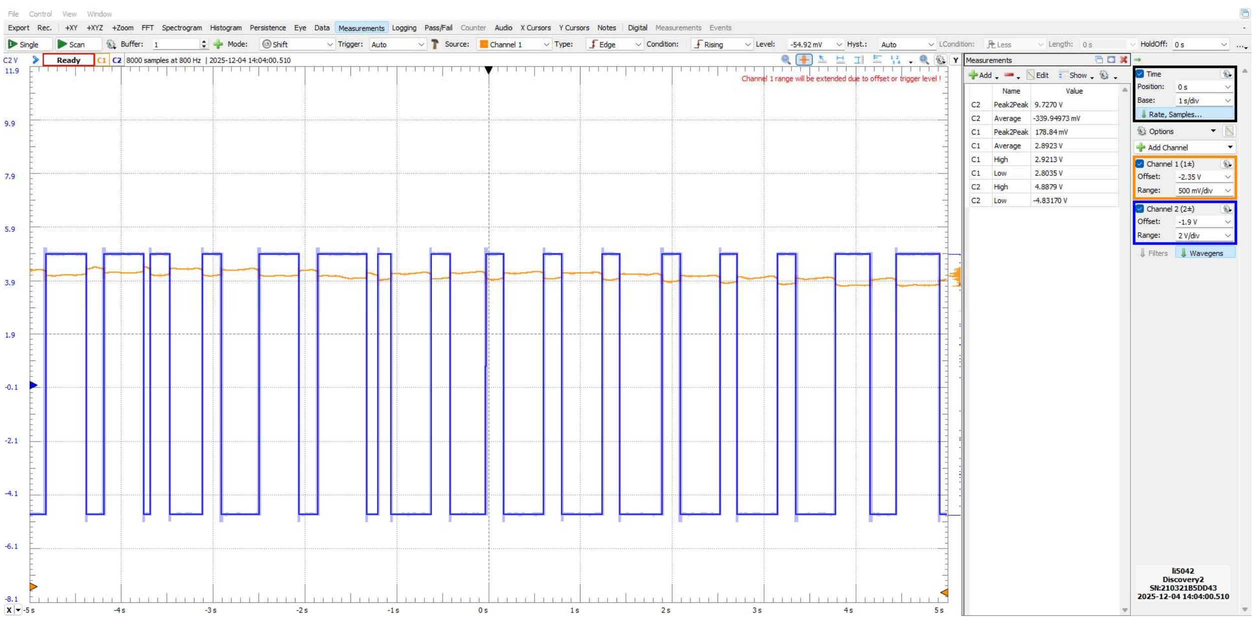

Figure 15: Oscilloscope of integrated circuit with finger put into IR sensor module. Input signal (orange) is the IR sensor output and output signal (blue) is the output of the comparator module.

The heart rate monitor works as expected: The heart rate input has a Vpp of 0.178 V with an DC offset of 2.89 V, which is expected. The higher Vpp just means that the signals will be cutoff by the power rails, but with a final comparator, it does not matter.

The comparator output was expected as well: The output had a high of 4.88 V and low of -4.83 V, making a Vpp of 9.727 and a DC offset of around 0V. This is as expected, and causes a working LED display indicator.

5. Conclusion:

The heart rate monitor worked as expected.

The necessary parameters were: gain between 100 and 1000, each stage has a gain of less than 100, the high pass filter has a cutoff of lower than 40 BPM, the low pass filter has a cutoff of higher than 200 BPM, and the LED has to be displayed visibly.

These parameters were all satisfied. Respectfully, the low pass had a gain of 11 times, the high pass had a gain of 11.1 times, and the overall bandpass filter had a passband gain of 40.8 dB = 109 times, which is within parameters. Also, of the overall bandpass filter, the low cutoff was 0.368 Hz = 22.08 BPM and a high cutoff of 5.37 Hz = 332.2 BPM, which also satisfies parameters. Lastly, the LED was visible when flashing when observing experimentally, indicating that the entire circuit worked as a whole.

Sources:

Lm324.Pdf, www.ti.com/lit/ds/symlink/lm324.pdf. Accessed 14 Sept. 2025.

LM339B, LM2901B, LM339, LM239, LM139, LM2901 Quad Differential Comparators, www.ti.com/lit/ds/symlink/lm339.pdf. Accessed 8 Dec. 2025.

Onsemi, www.onsemi.com/pdf/datasheet/rfd3055lesm-d.pdf. Accessed 6 Sept. 2025.