University of Washington
Department of Electrical Engineering
EE 436, Spring 2019

Medical Instrumentation Lab 1:
Design of an Optical Heart Rate Monitor

Student Name	**Laboratory Contribution**
Minh Ho	Design, Simulation, Construction, Testing, Lab Report
Landon Kruse	Design, Construction, Testing, Lab Report

May 12th, 2019
Professor Lawrence Lam, PhD

Table of Contents

Abstract

This report covers the designing, building and testing of a transmission type Photoplethysmography (PPG) device for detecting a subjects heart rate due to the changing in volume of blood vessels over time due the the pumping of a subjects heart. Due to the small change in signal over time modules for amplifying and conditioning the signal are also designed and built.

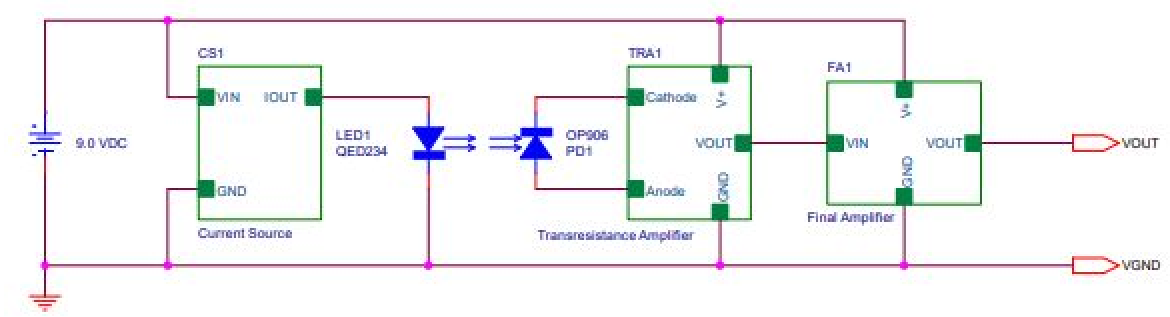
Introduction

Photoplethysmography is a technique using light to measure the systematic expansion and contraction of blood vessels in tissue. This successful measurement of the heart rate can be achieved by either shining a light through a thin enough tissue (such as the finger tip or earlobe) or can be reflected into tissues and back to an appropriate sensor on a location such as the wrist. This project focused on the transmission version of the measurement, specifically through the finger and all of the associated signal conditioning and amplifying needed to get a usable signal out and measure the subjects heart rate.

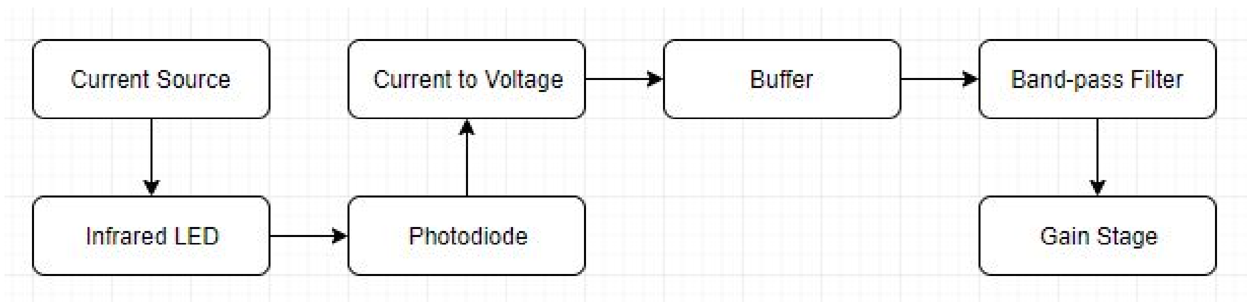
Background

Measuring the various signals the body produces can paint a picture of the state that that body is in. Normally the approach to diagnose machines would be to open them up and pinpoint a problem or desired signal directly. This approach obviously has some drawbacks for diagnosing a living breathing human where the cost and danger involved in opening them up is prohibitive, so less direct approaches must be taken to glean information on how the body is functioning. Pulse rate can tell a lot about the state that someone is in, and Photoplethysmography (PPG) is a low cost and non invasive way to capture the body's heart rate by measuring the difference in light passed through tissue.

Block Design



Circuit Block diagram from Project 1 instructions



Block diagram for our intended circuit design

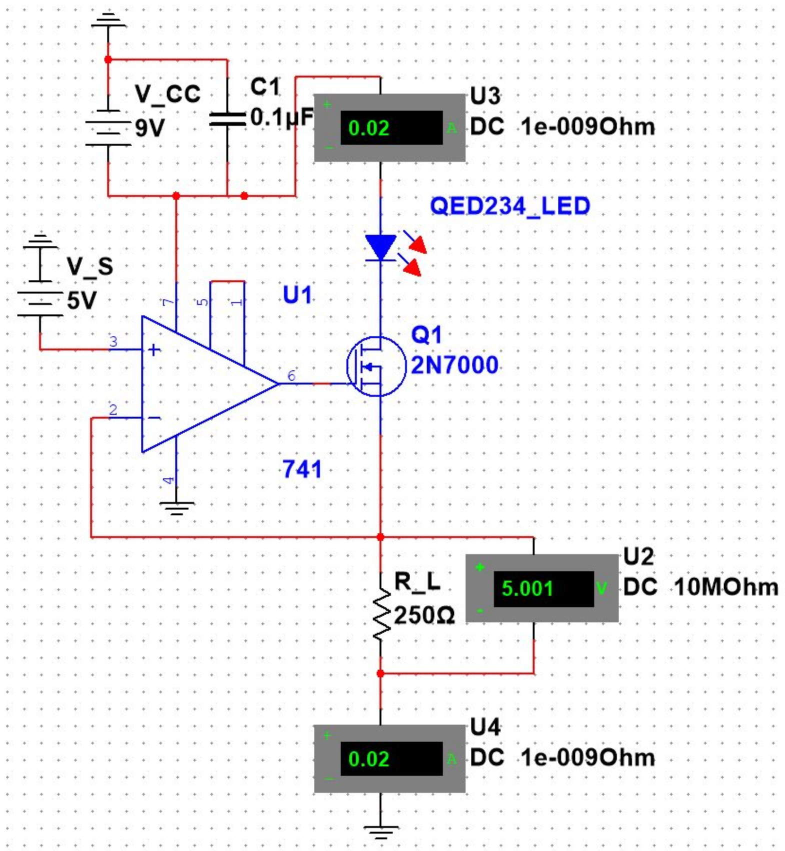
The circuit block diagram outlines the different stages of the circuit that are needed to get the desired signal. With a single voltage source (9v) each stage is referenced to 4.5v as a virtual ground allowing for a positive and negative swing in a voltage signal. A constant current source is needed to power the infrared LED at a constant 20mA to ensure consistency in measurement. A transresistance amplifier is needed to amplify and convert the reverse bias current in the photodiode into a voltage signal that can be passed to other stages for filtering and amplification.

The voltage signal then needs to pass to a bandpass filter to both filter out DC and near DC signals and the higher frequency noise that is constant in the environment (like 60Hz, 120Hz, and higher). Finally there is a gain stage to get the signal to 1Vpp to be read by an oscilloscope.

Simulation and circuit modules

Constant current source and infrared LED

The design specifications ask us to establish a constant current of 20 mA through the LED. Using a MOSFET in conjunction with an op-amp, we designate a voltage at the source of our NMOS transistor as the voltage source. We use the properties of the transistor to allow a range of voltage drops from our positive rail to our source value. Using a load resistor we can then designate the current through the circuit using Ohm's Law.



Current source MultiSIM simulation

In this case we want a 20 mA current from a 5 V source as we wanted to use a 5 V regulator we had available from our lab kit. The load resistor required for create the 20 mA current source is therefore 250 Ω as shown in the simulation above.

Photodiode and transresistance amplifier

From the light emitted from the infrared LED, we want to capture the changes in the finger's capillaries and blood vessels caused by our heart beating. We can see these changes from light captured from a photodiode on the other side of the finger from the LED.

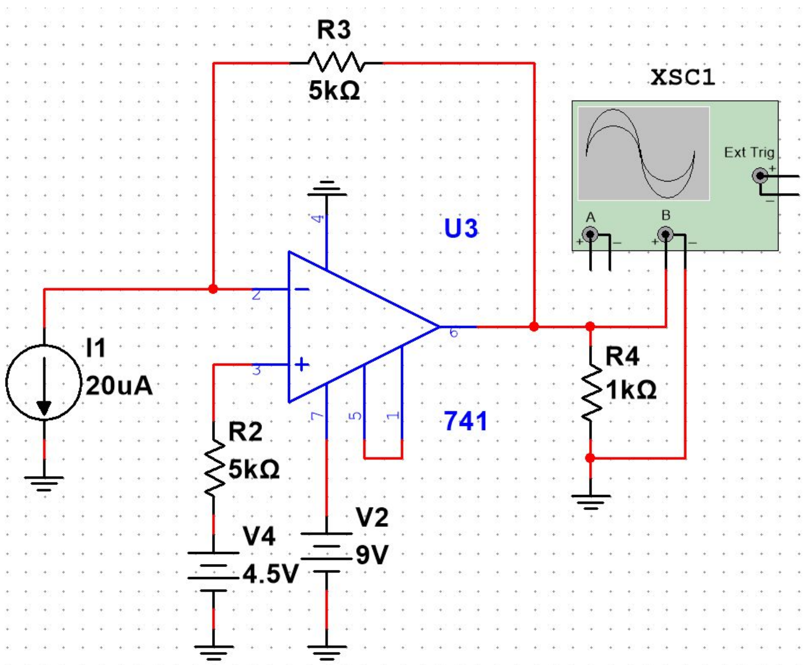
Photodiodes operate in reverse bias mode and produce a small current proportional to the level of light that is captured. This small current and its known response can be used in conjunction with the appropriate transresistance amplifier to produce a voltage signal that represents a person's heart beat.

Electrical Characteristics (T_A = 25° C unless otherwise noted)

SYMBOL	PARAMETER	MIN	TYP	MAX	UNITS	TEST CONDITIONS
I_L	Reverse Light Current OP905 OP906	 14 16	 - -	 32 35	µA	V_R = 5 V, E_E = 0.50 mW/cm^2 (3)

OP906 characteristics taken from datasheet

Taken from the datasheet for the OP906, we know that the operating range for the reverse light current of photodiode is between 16 and 35 uA in reverse bias.

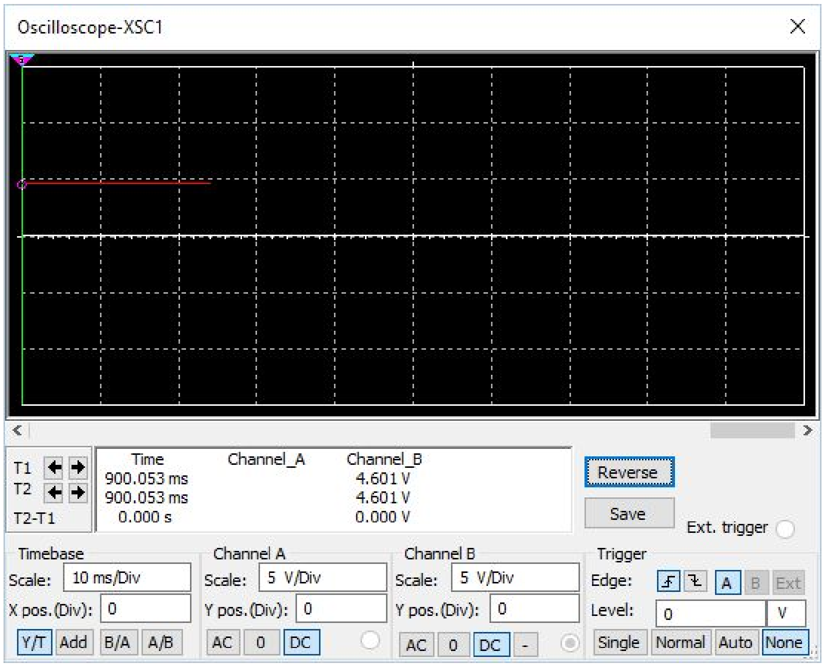


Current to voltage converter

We use a current to voltage converter with an effective ground voltage of +4.5V. The project specifications asks for a voltage signal of 100 mV at the output of the opamp.

$$V_{out} = -I_{diode}R_f$$

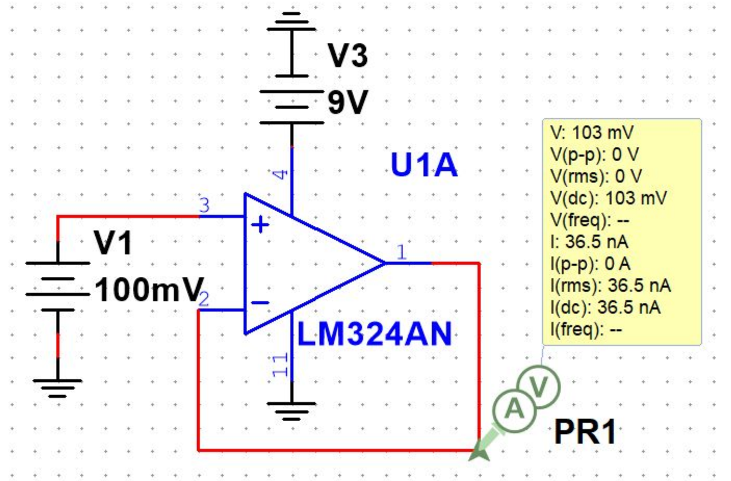
We simulate the photodiode with a current source in the opposite direction as it functions in reverse bias.



Using the oscilloscope simulation tools in MultiSIM, we see that we have an output of 4.601 V at our load. This is the +4.5 ground voltage with the 100 mV output.

Buffer

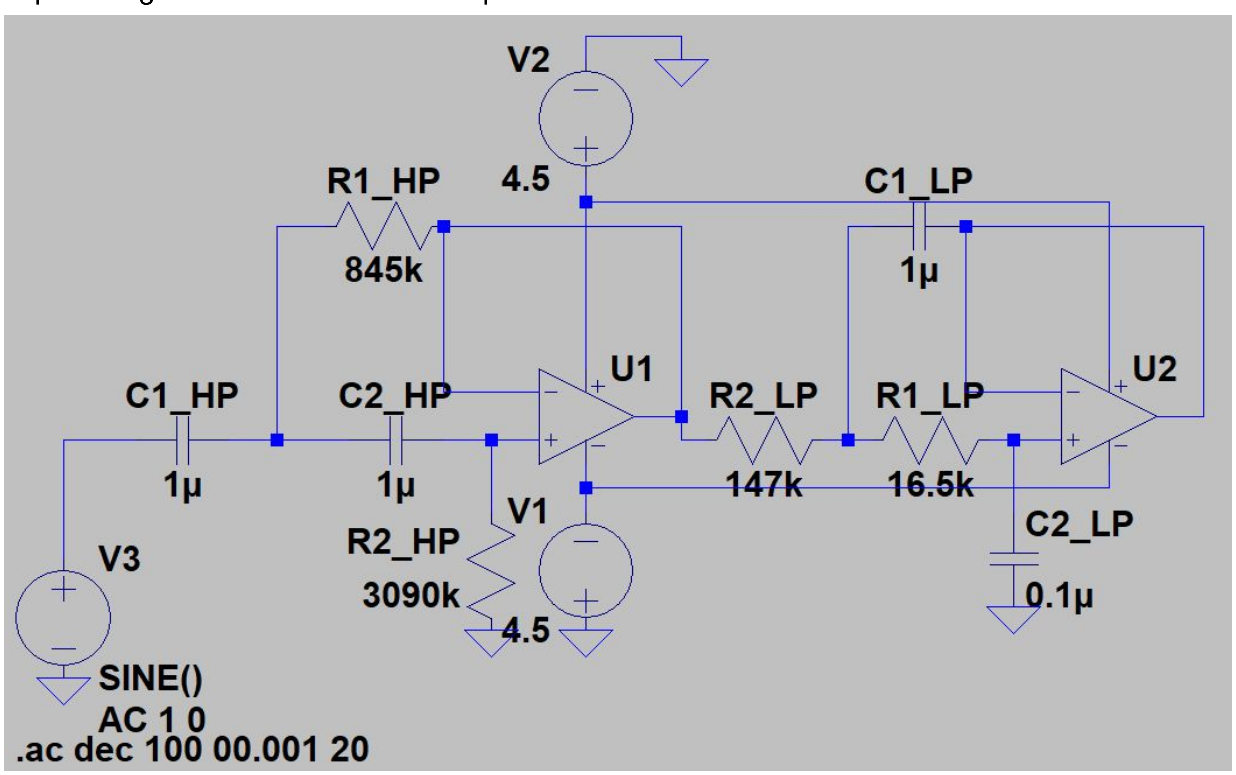
After we have our voltage signal from the transresistance amplifier, we include a buffer stage to give a high input impedance for our signal into the next stage of our circuit. The buffer contains a near infinite input impedance and low output impedance. At the output, the buffer acts as an ideal voltage source with fewer impedance problems.



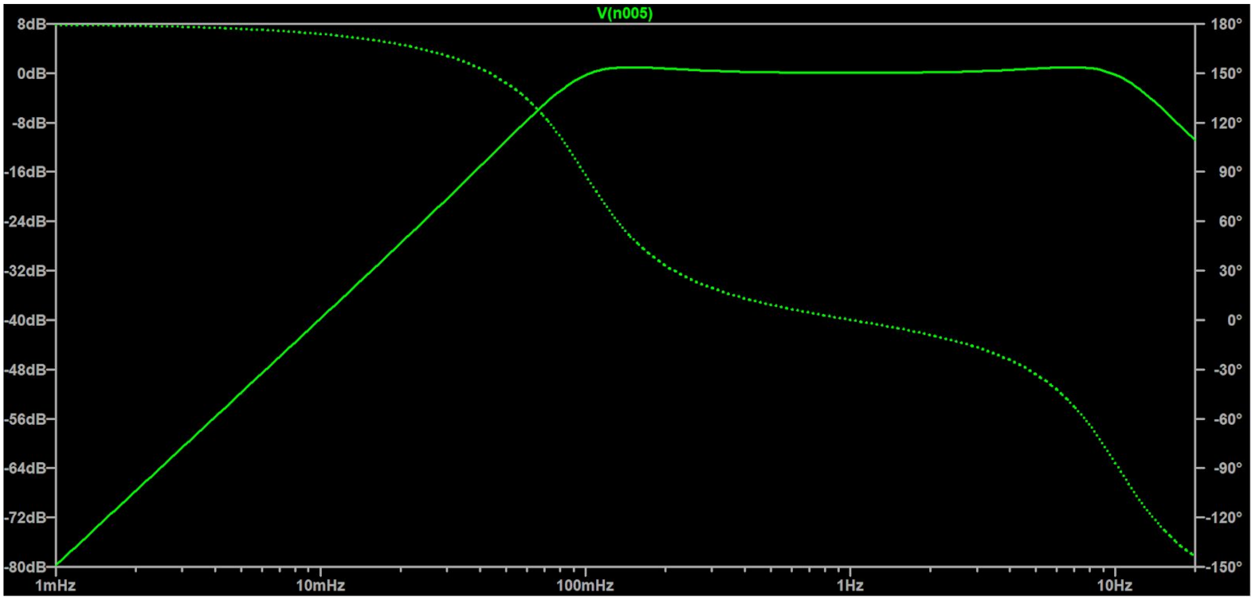
Bandpass Filter

The normal heartbeat for humans are between 1 and 3 Hz. We want to filter out all other noise that our circuits could pick up. Using a bandpass filter, we limit the signals to between 0.1 and 10 Hz per the project specifications. This filters out the most common environmental noise frequencies (60Hz and 120Hz).

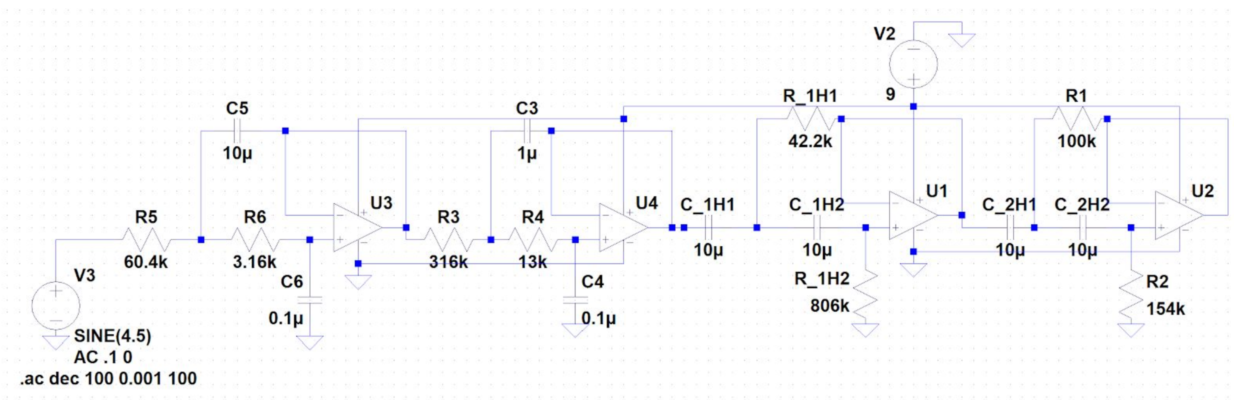
Our simulation is performed in LTSpice due to the AC sweeps being easier to set as well as the output being more nice to look at compared to MultiSIM.



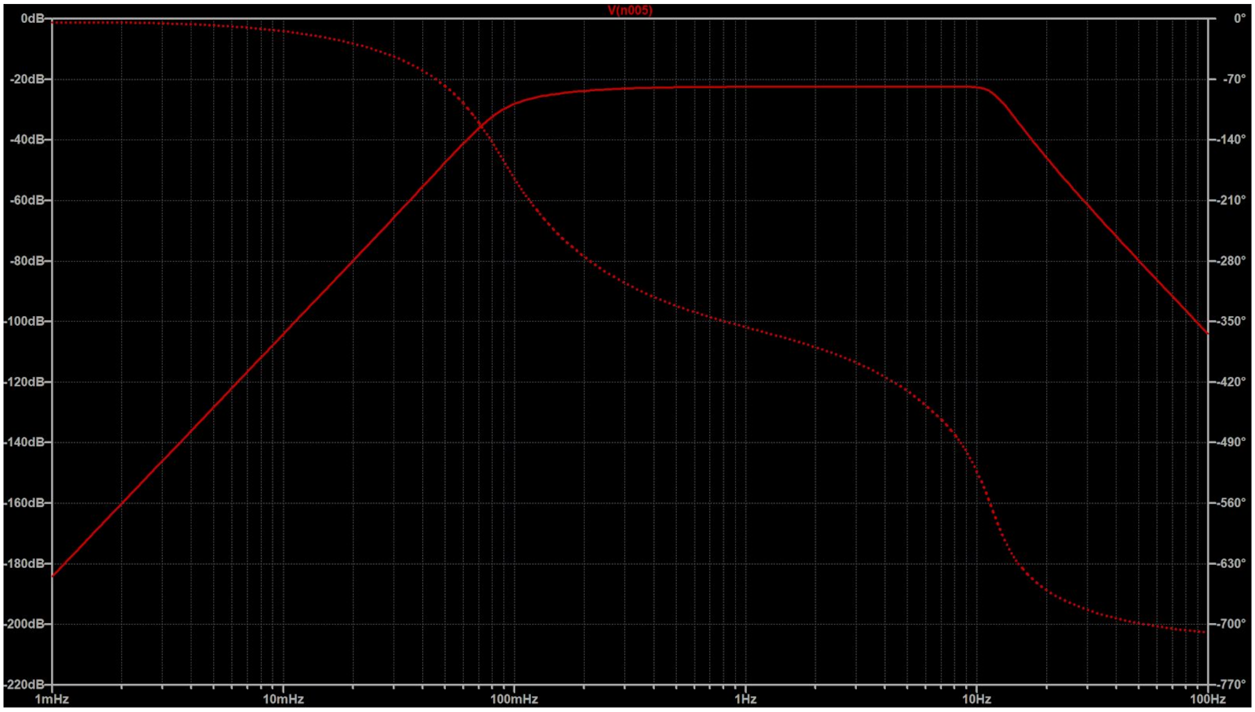
LTSpice schematic of our 2nd order bandpass filter



LTSpice AC sweep of our 2nd order bandpass filter



LTSpice schematic of our 4th order bandpass filter

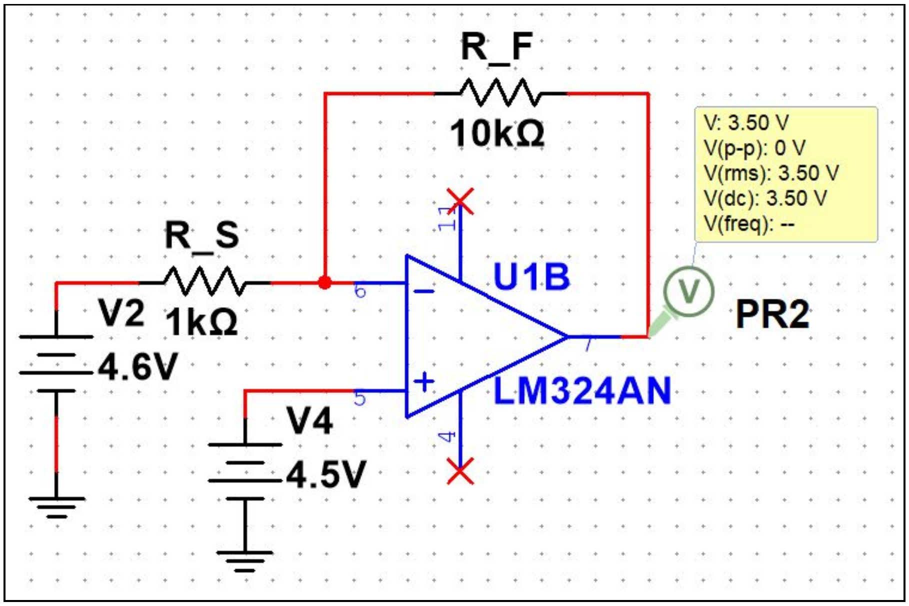


LTSpice AC sweep of our 4th order bandpass filter

We are unsure why the 4th order bandpass filter simulation has a -20 dB loss within the active band. Building the circuit, we still have full signal strength within the band.

Gain stage

In the final stage of our circuit, we have a gain stage to amplify the signal. The project calls for a voltage gain of 10 either inverting or non-inverting. In our design we use an inverting amplifier with a feedback resistor of 10kΩ and a source resistor of 1kΩ. We also need to make sure the circuit has the same ground reference of +4.5V as the rest of the circuit.

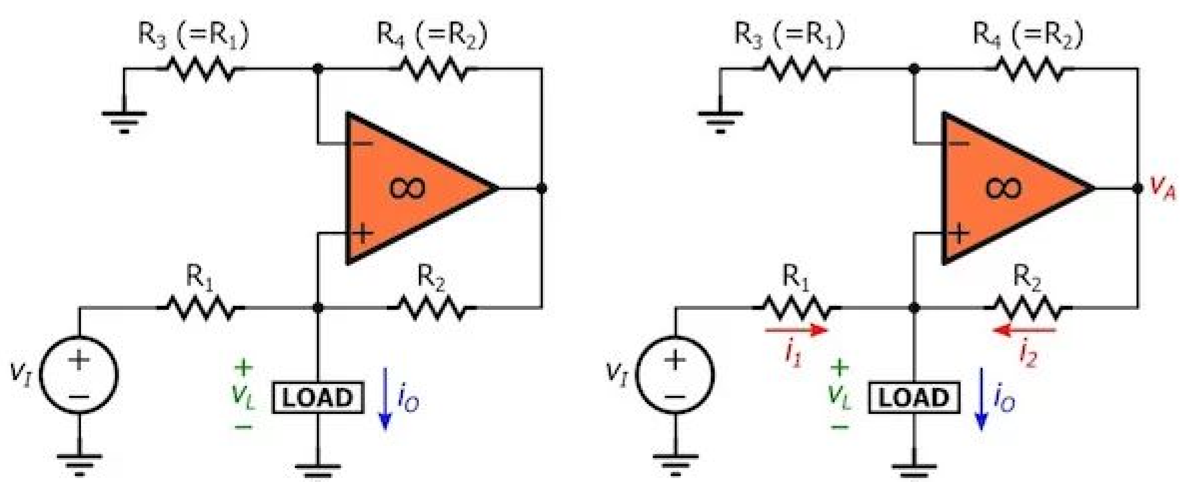


In the figure above we have the MultiSIM simulation of the gain stage of our circuit. With a ground reference of 4.5V, we expect to see a 1V drop at our output due to the circuit due to our 100 mV input and design for a gain of 10. With our new virtual ground, +3.5 V is equivalent to -1 V.

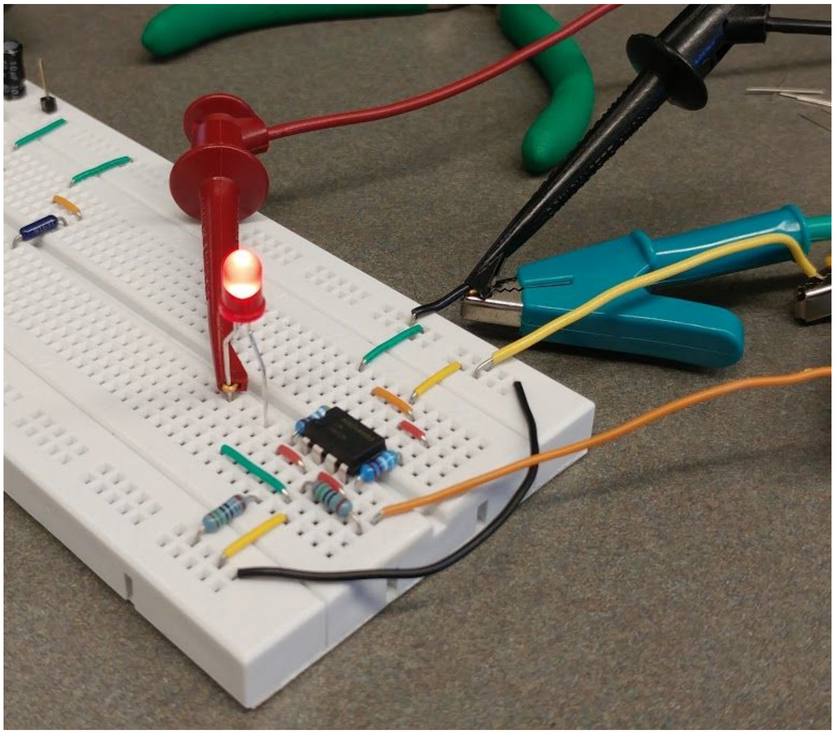
Prototype Construction and Results

Constant Current Source

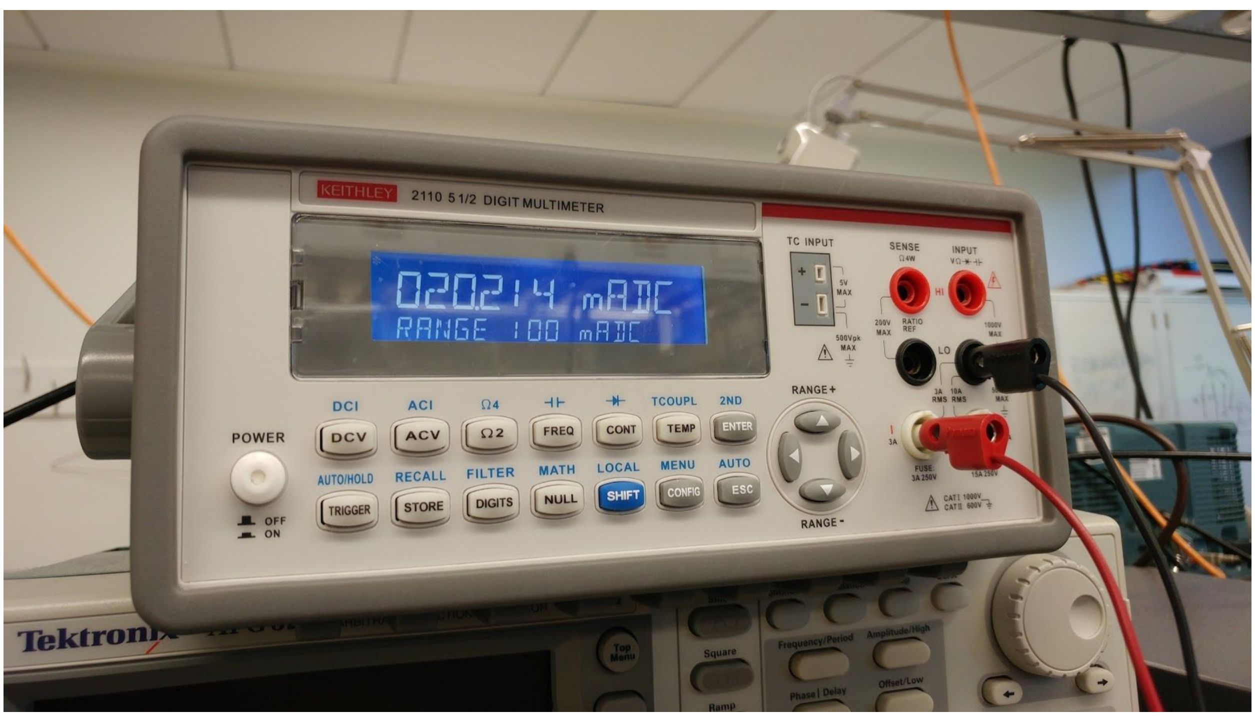
Initial construction started on the current source for the infrared LED. Based on research online into Op-Amp constant current sources the first circuit built and tested was the Howland Current pump which utilized 4 resistors to set the desired current through the load.



Howland current pump

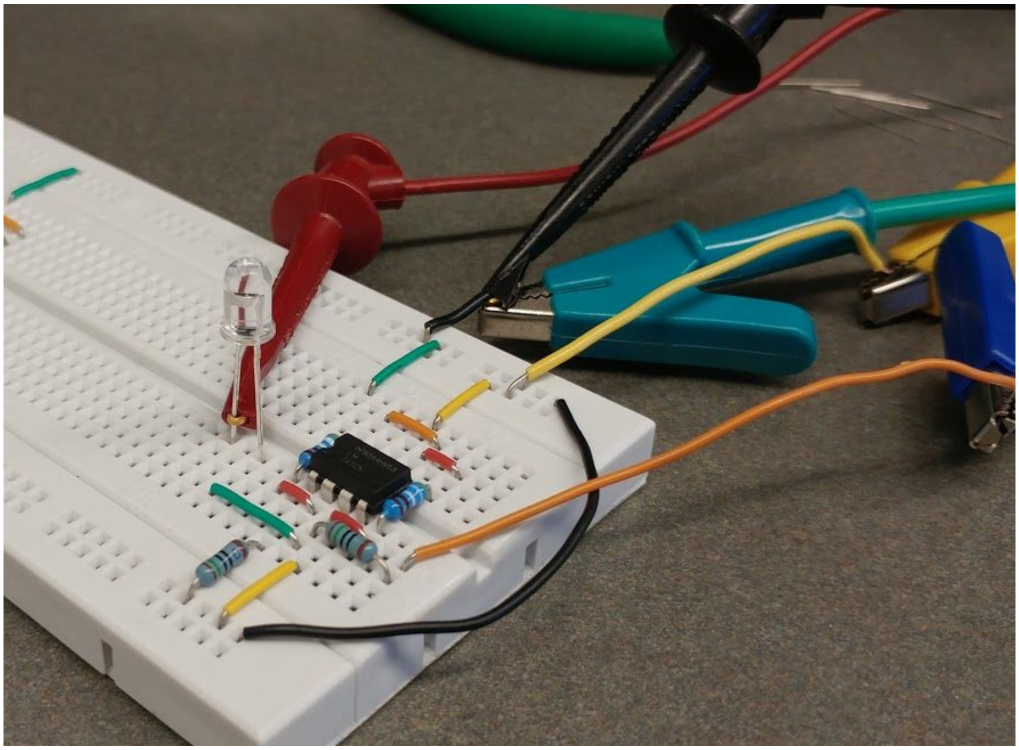


Howland current pump test circuit with red LED

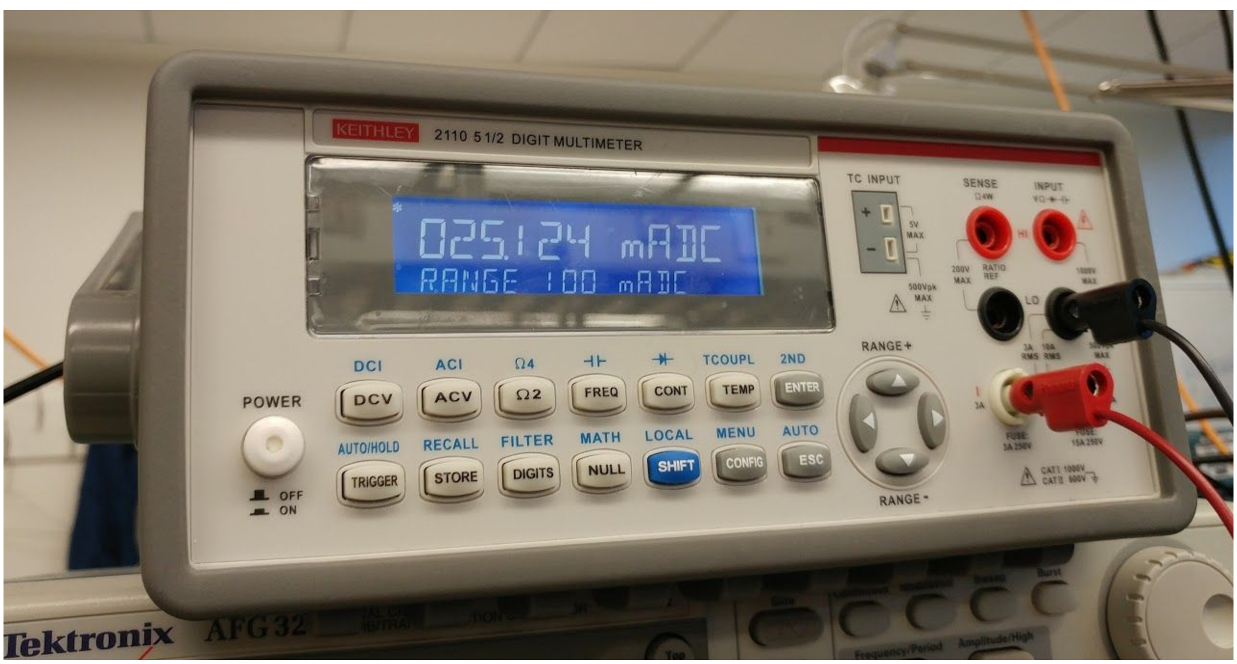


Howland current pump with red LED current output

The Howland current pump worked well for the red LED outputting the desired 20mA of current to drive the LED. However when the Infrared LED was tested the output current was 25mA.



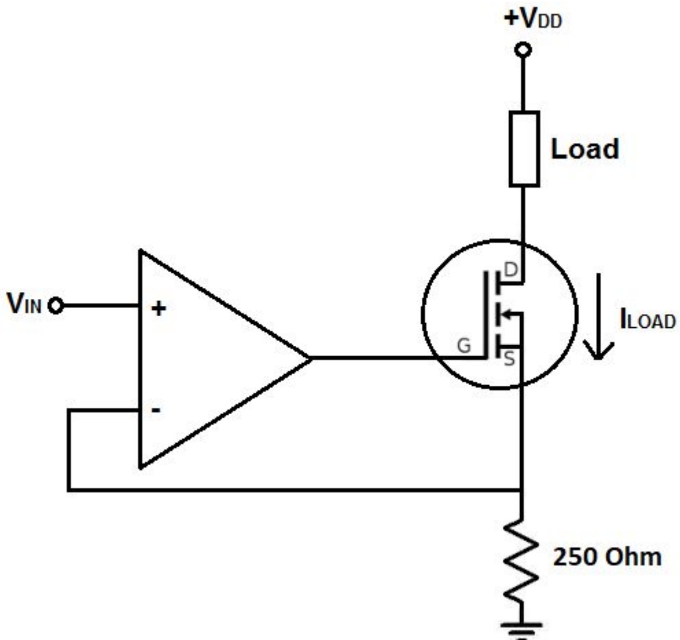
Howland test circuit with infrared LED



Howland infrared LED test circuit current output

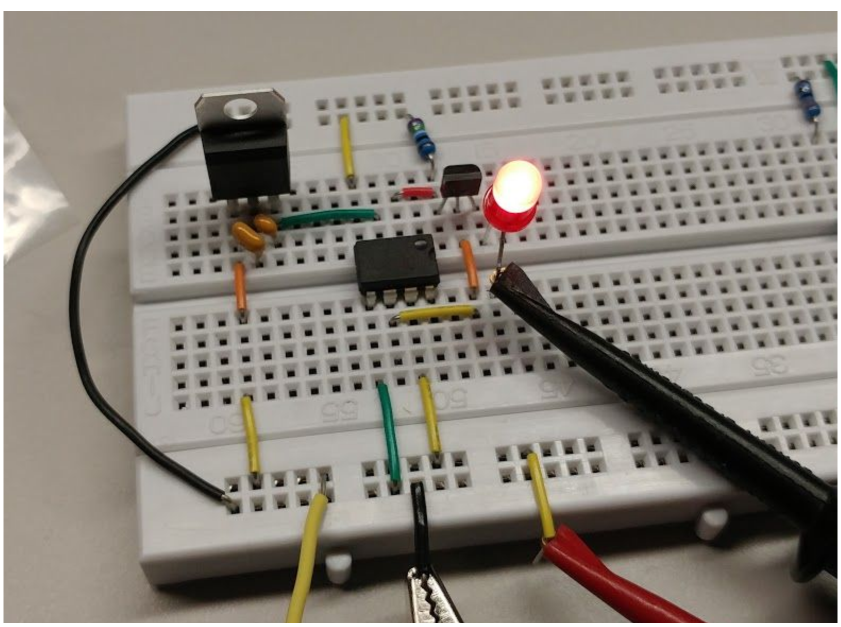
Due to the differences in the current draw for both LEDs, another constant current source was looked at based on the design followed by the wrist sensor group. This circuit utilized a

MOSFET and a selected resistor (250Ω) to set the output at a constant 20mA regardless of the load.

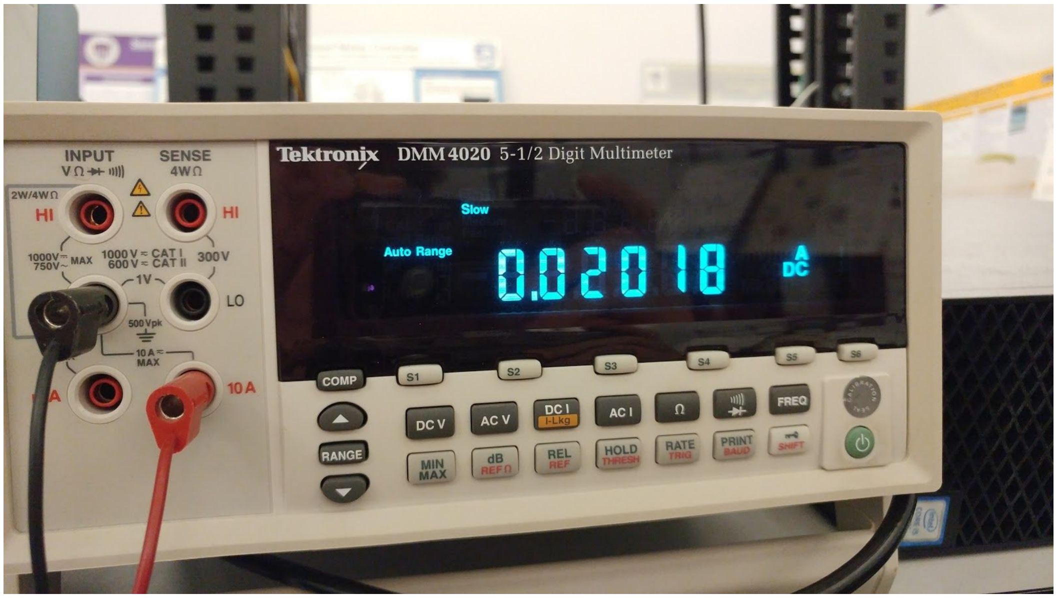


MOSFET constant current source schematic

To keep the Vin voltage constant (and therefore a constant current) a 5V linear regulator (L7805ABV) was used. Testing was done with both the normal and infrared LEDs to ensure a 20mA output current.



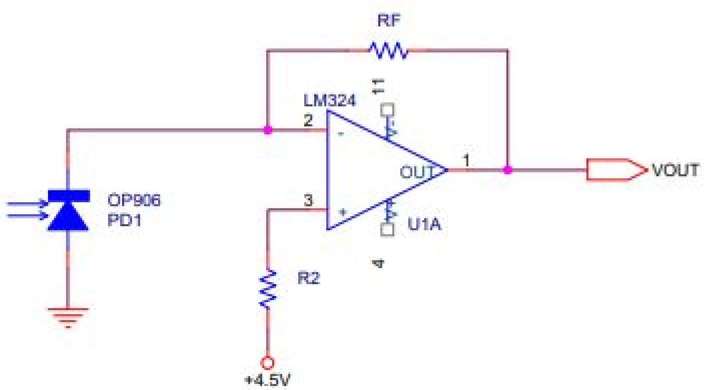
MOSFET constant current source test circuit



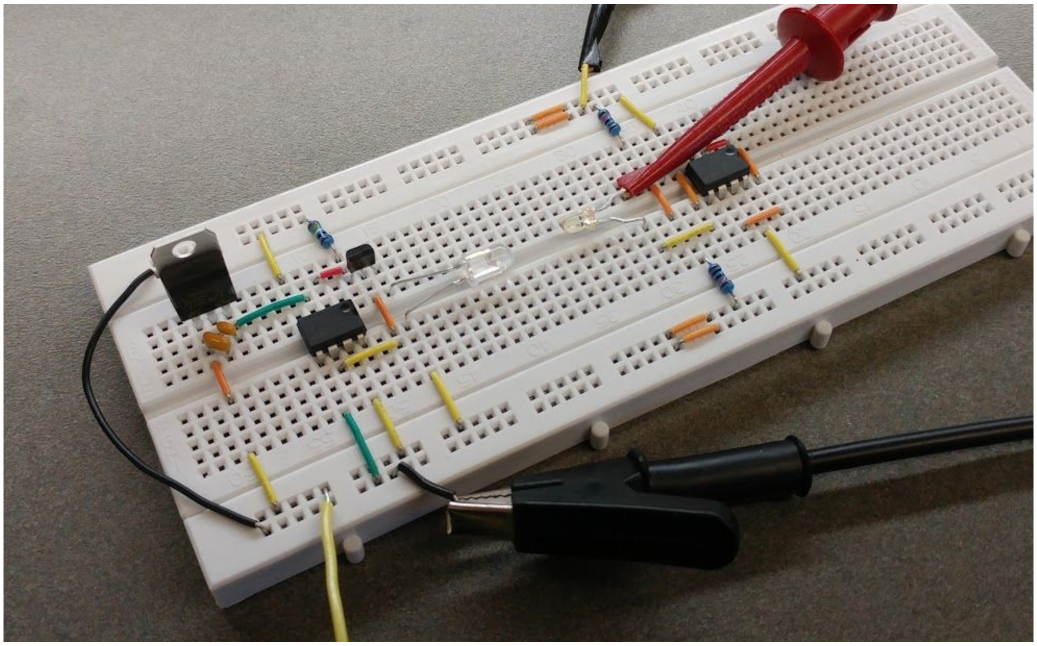
MOSFET constant current source output (Red and Infrared LED similar)

Transresistance Amplifier

The next circuit element that was prototyped was the transresistance amplifier for converting the reverse bias current of the photodiode into a voltage signal that could be filtered and amplified. The datasheet stated the reverse bias current as 15μA to 35μA. Using the current source and the infrared LED the transresistance amplifier circuit was built with the bias voltage set by a resistor divider network.



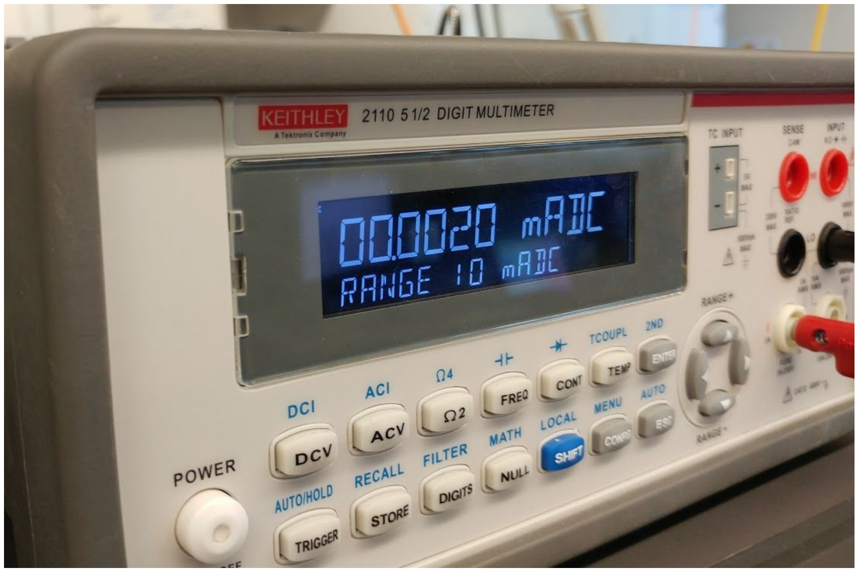
Suggested Transresistance Amplifier layout



Photodiode test circuit

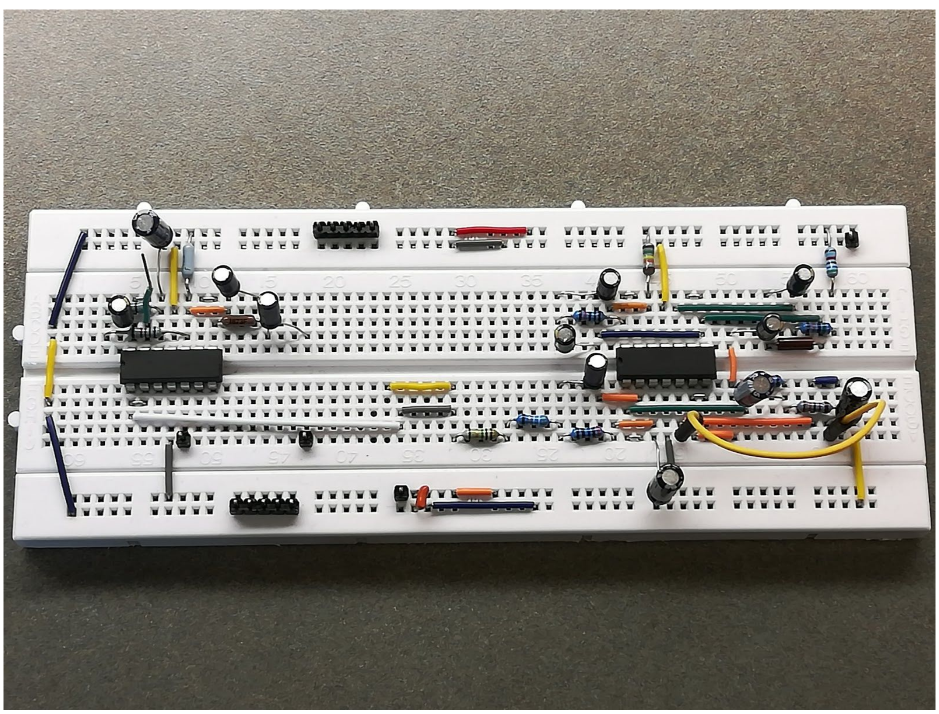
The test circuit was built to be close to the distance that the LED and photodiode would be at in the final version of the finger pulse sleeve. To test the true (not based off of the photodiode datasheet) currents being output through the photodiode, the entire test circuit was covered with a lab approved light blocking material (a jacket) and current readings were taken with and without a finger in the way of the sensor.

Dark test current output with infrared LED (no obstruction)



Dark test current output with infrared LED (finger between infrared LED and photodiode)

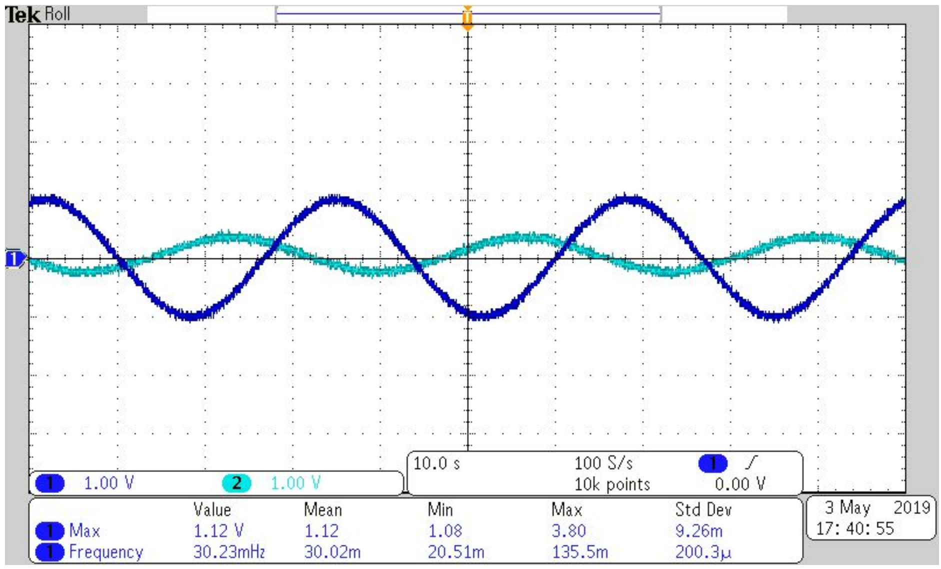
Bandpass Filter and Amplifier



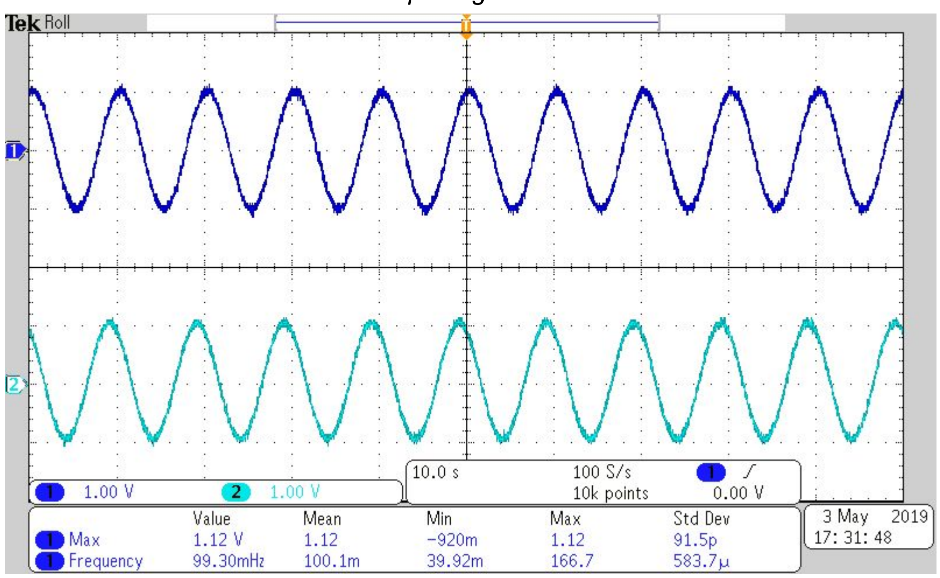
Buffer and 4th order bandpass filter circuit using 2 LM324 quad op amps

The 4th order bandpass is on the right side of the breadboard. The buffer is on the bottom left of the left op-amp. There is also a 2nd order bandpass filter in the top left for testing. There includes a bypass capacitor from our positive rail to ground for filtering out any AC sources from the power supply.

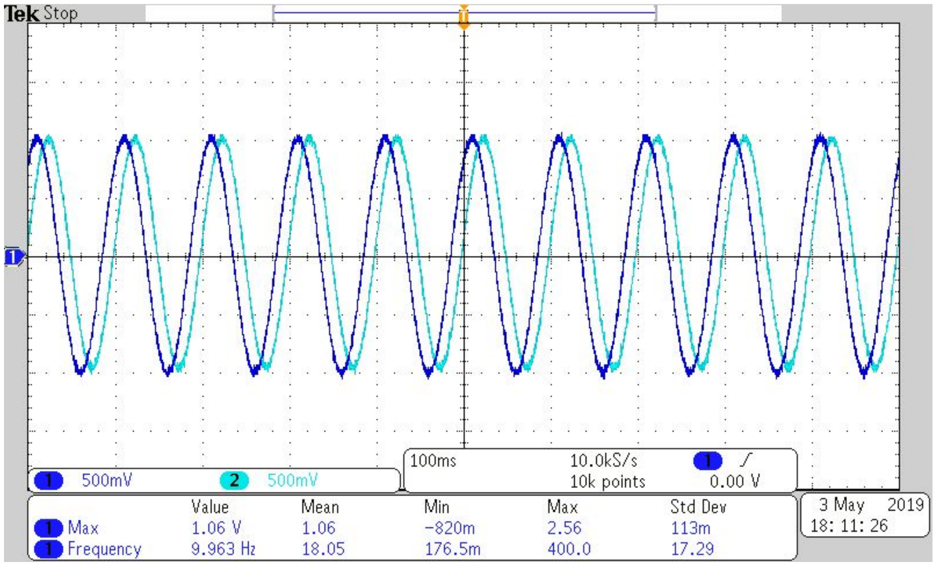
The outer rails on both sides of the breadboard are at the virtual ground of +4.5 V. The inside of the top rail is the actual ground while the inside of the bottom rail is +9.0 V.



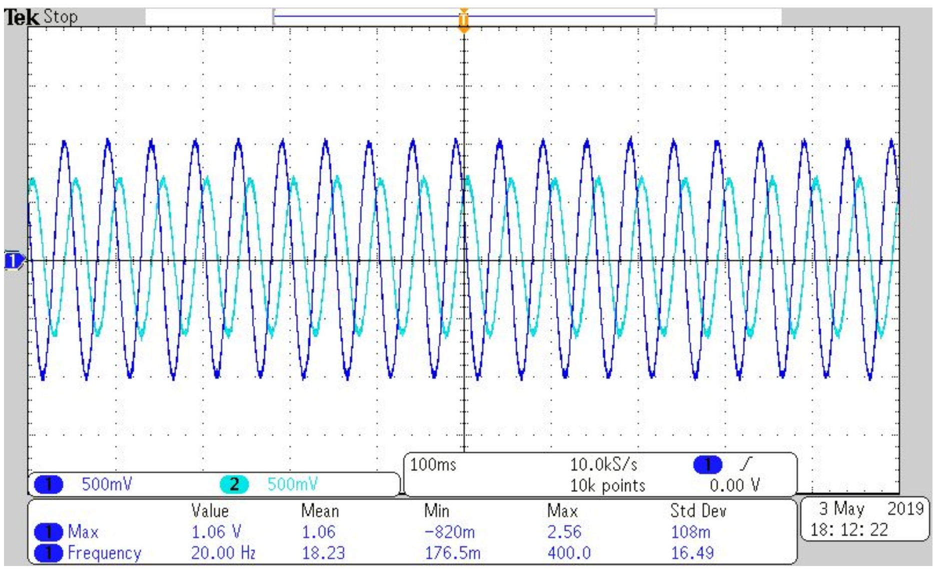
Filter w/ input signal at 20 mHz



Filter w/ input signal at 1 Hz



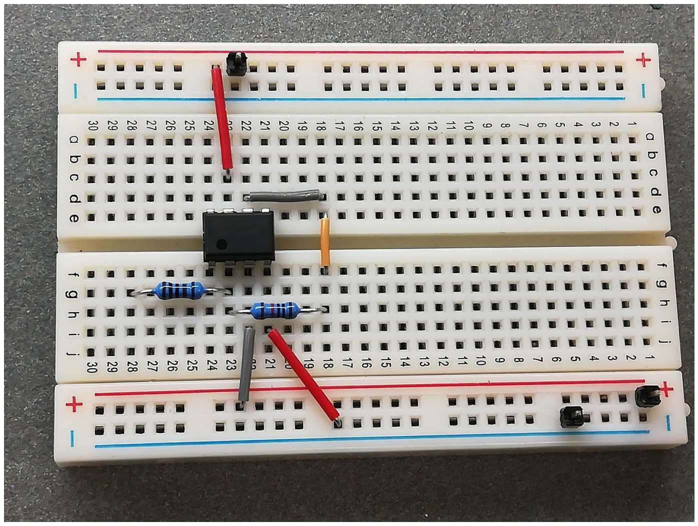
Filter w/ input signal at 10 Hz



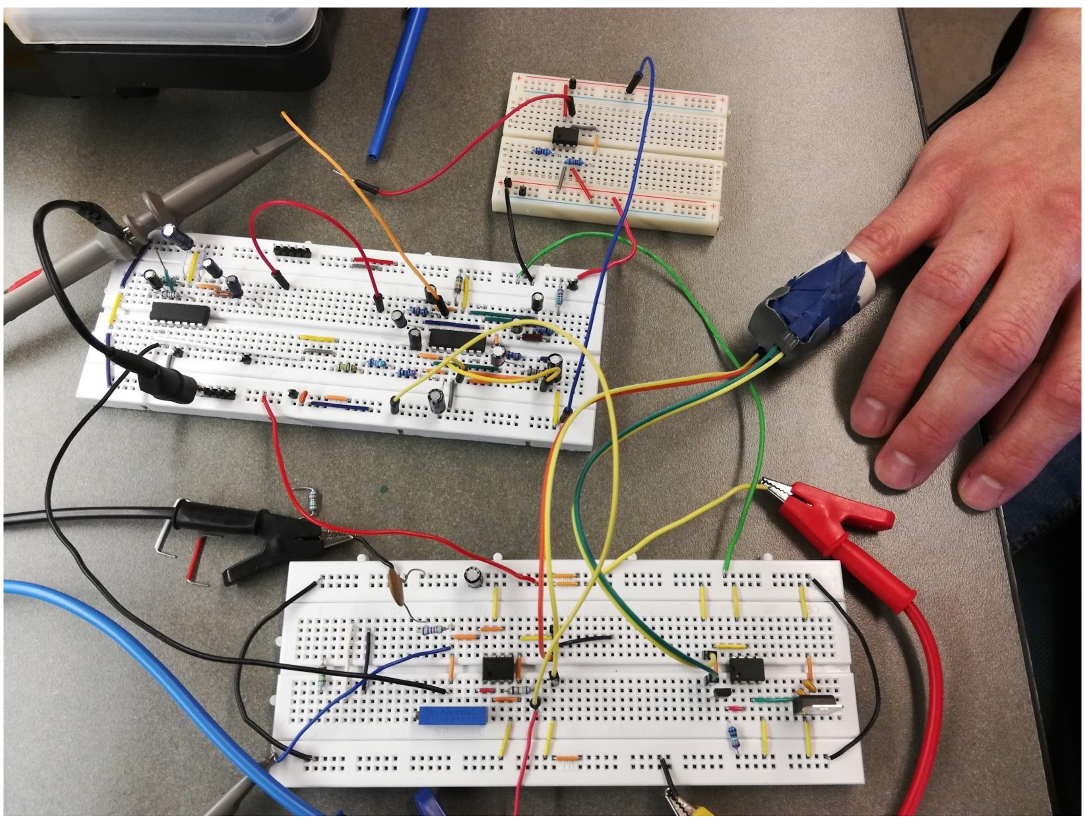
Filter w/ input signal at 20 Hz

Testing the 4th order filter using the function generator and oscilloscope in the lab, we see that the filter accepts signals between 1 and 10 Hz before it starts to roll off and attenuate.

The design asked for a cutoff frequency of 1 Hz and 10 Hz for a -3dB loss. Our design did not meet these requirements with full signal strength at the cutoff frequencies. Improvements could be made in the design with difference component values to account for this.



Circuit layout for the inverting 10x amplifier stage



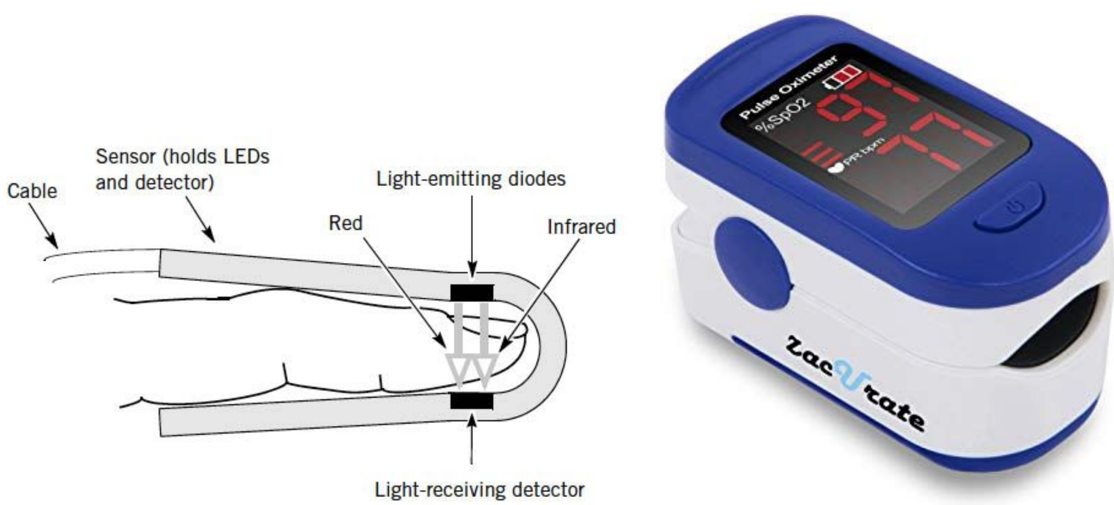
The entire circuit together ready to test

Entire circuit layout with all circuit modules wired together (input on bottom, buffer and filter center, gain and output up top)

20 hours of lab time later

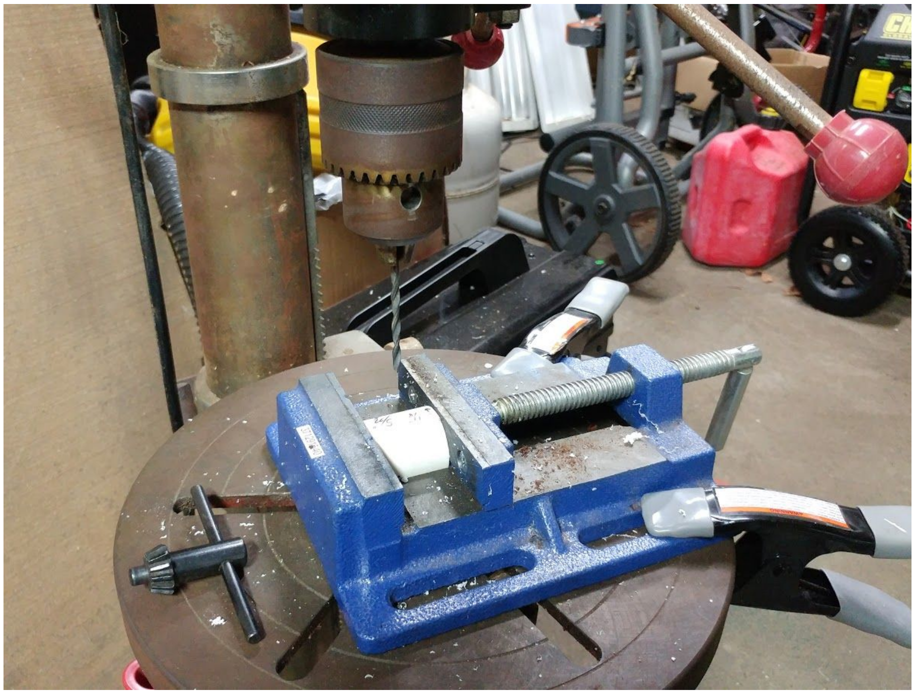
Finger Apparatus

In order to get a signal through the test subjects finger of the changing blood flow and thereby their heartbeat, the light source and the detector need to be aligned very closely. The distance needs to remain constant and on a spot on the subjects finger right behind the nail on the cuticle.

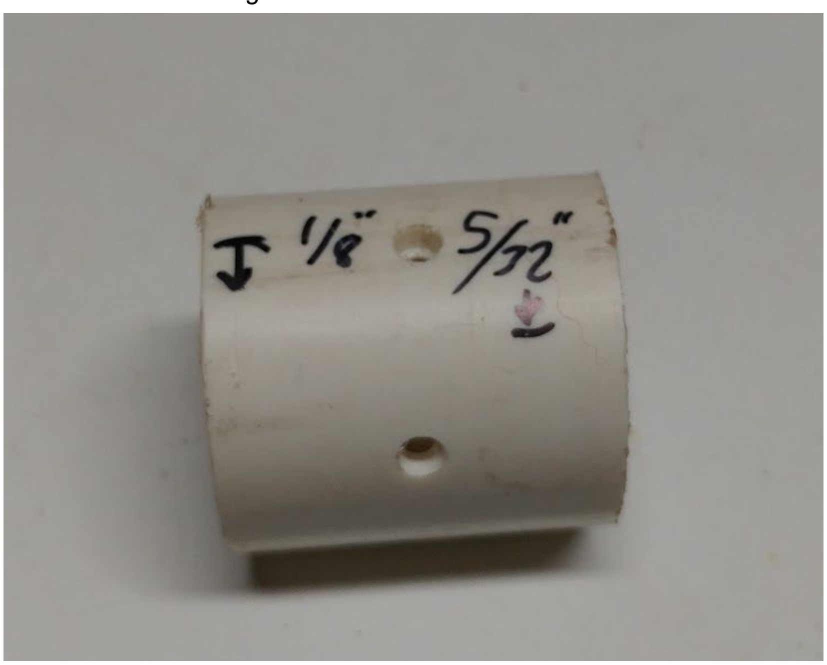


Conceptual structure of the device (pulse oximeter) - (acuclinic.com.au, Amazon.com)

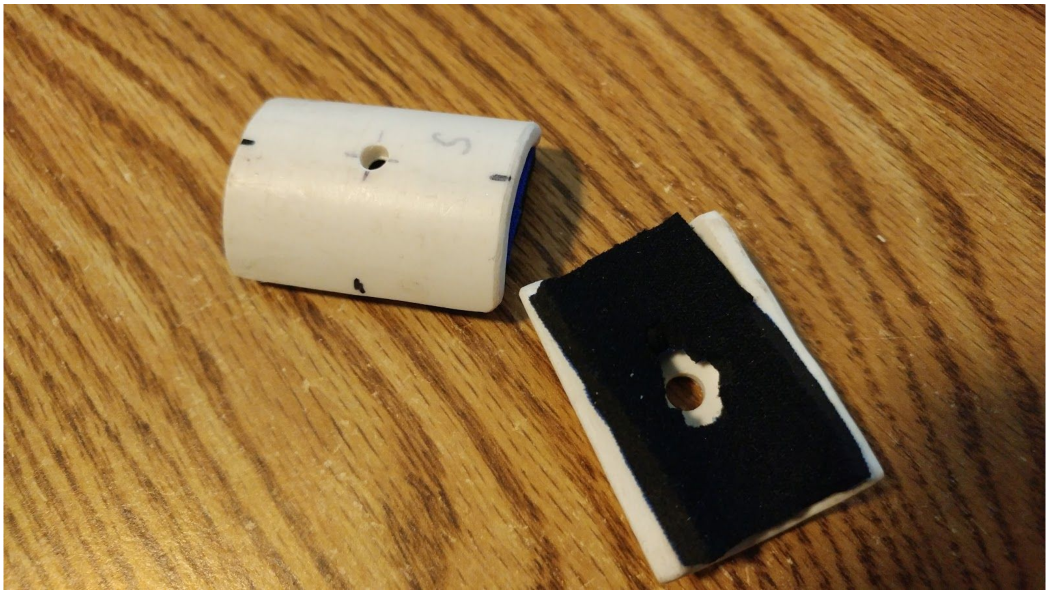
The initial design was set up similar to what a common pulse oximeter is set up like, essentially a clamp that closes around the subjects finger. The infrared LED and sensor would align and some soft material would block outside light leaving only the infrared light to trigger the sensor.



Testing drill bit sizes for sensor and LED

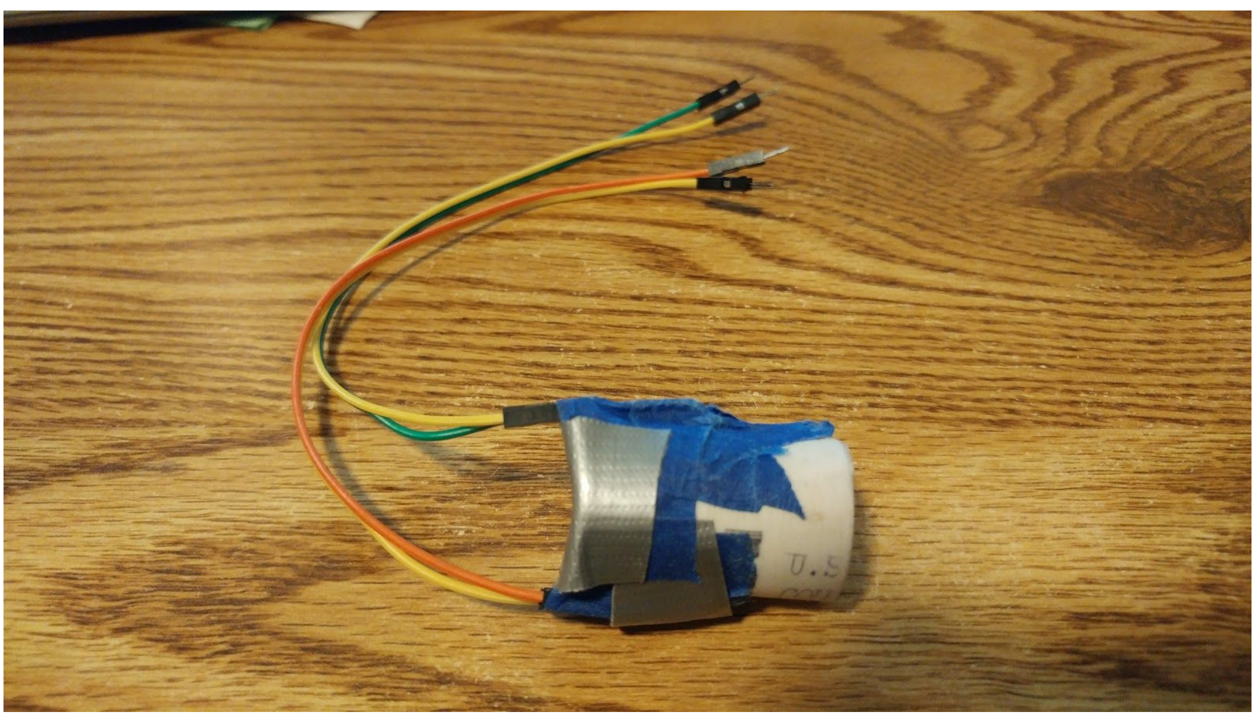


PVC test piece specifying bit sizes for the LED hole

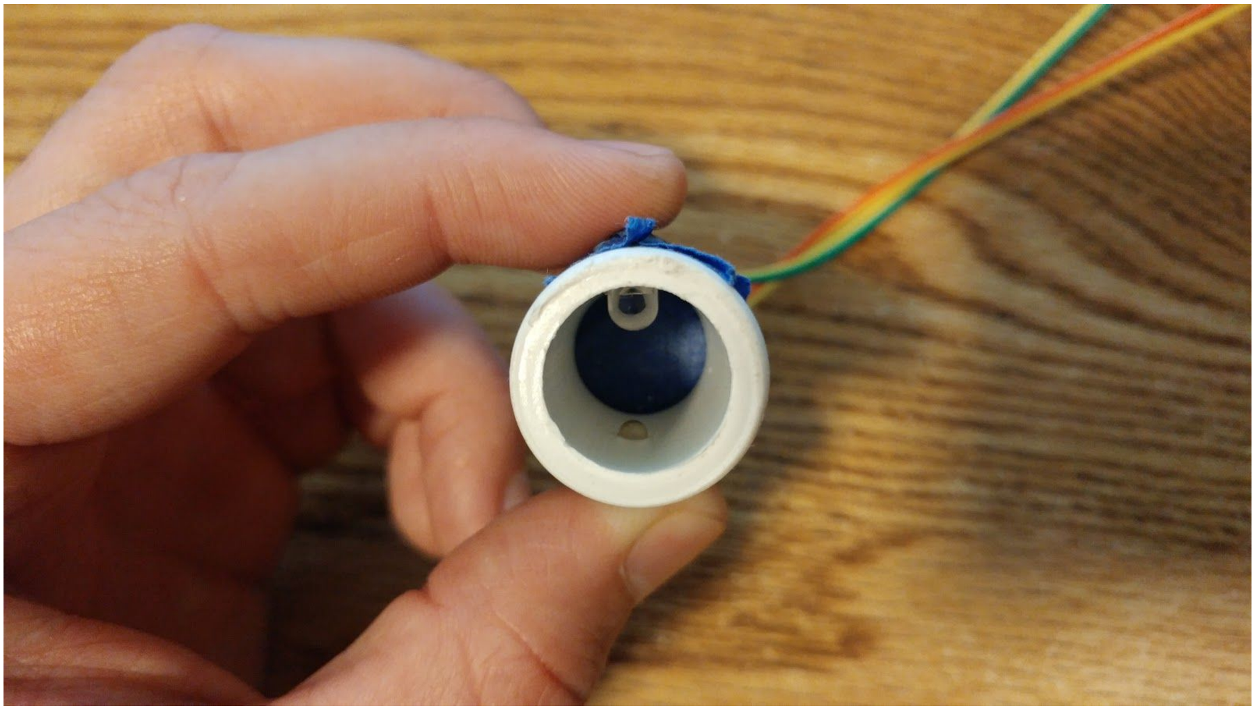


First attempt finger sensor with neoprene material for light blocking

The first attempt design was a failure because direct alignment of the light source and the sensor was much more important than anticipated, though the spacing of the sensors was just right and the stepped down holes were used in the final version.



Final version of the finger apparatus (yellow wire is anode for both sensor and LED)

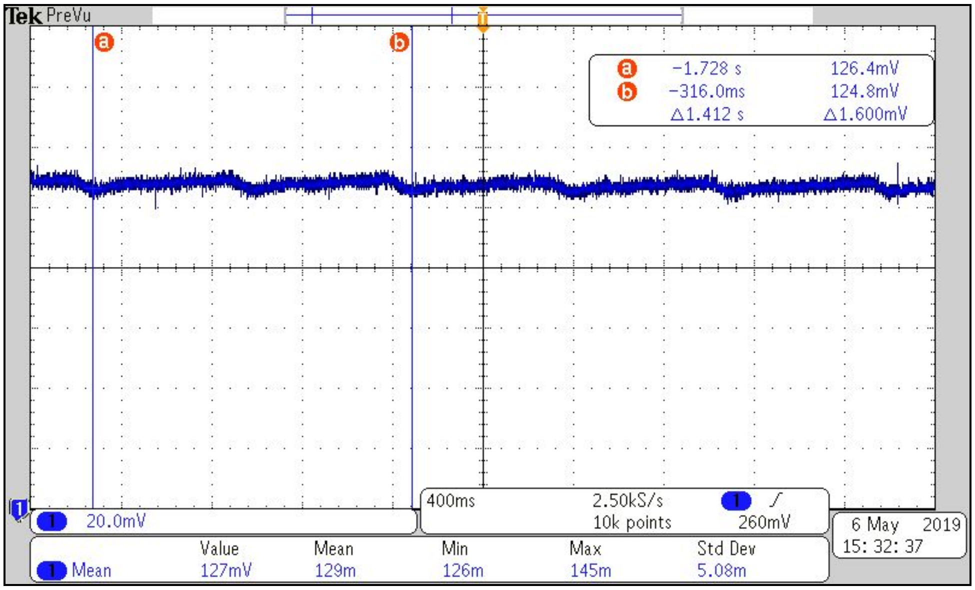


Inside spacing and alignment of the LED and sensor

The final version of the finger sensor is made of a smaller piece of PVC to ensure there is contact of the LED and sensor with the surface of the skin on the finger. The end of the tube is taped off with thicker duct tape to stop any external light from getting to the sensor and throwing off the measurement. This version provided a signal but one much smaller than we anticipated (1mV vs 100mV). Though the alignment was consistent, the sensor and the LED were still not quite aligned perfectly and so the signal was reduced.

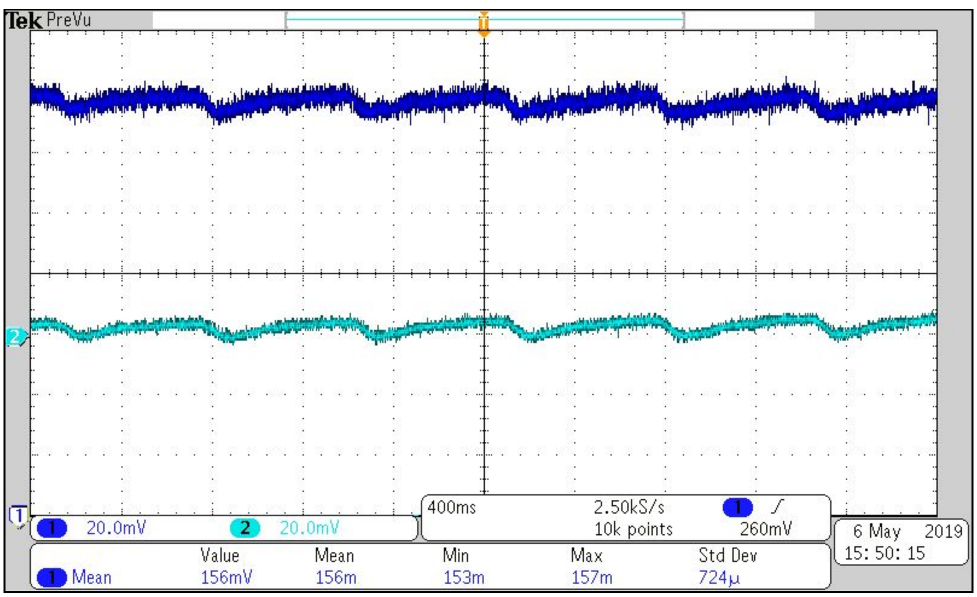
Signal results

Below are the signal outputs of our circuit tested in a real life environment using the PVC finger contraption we built.



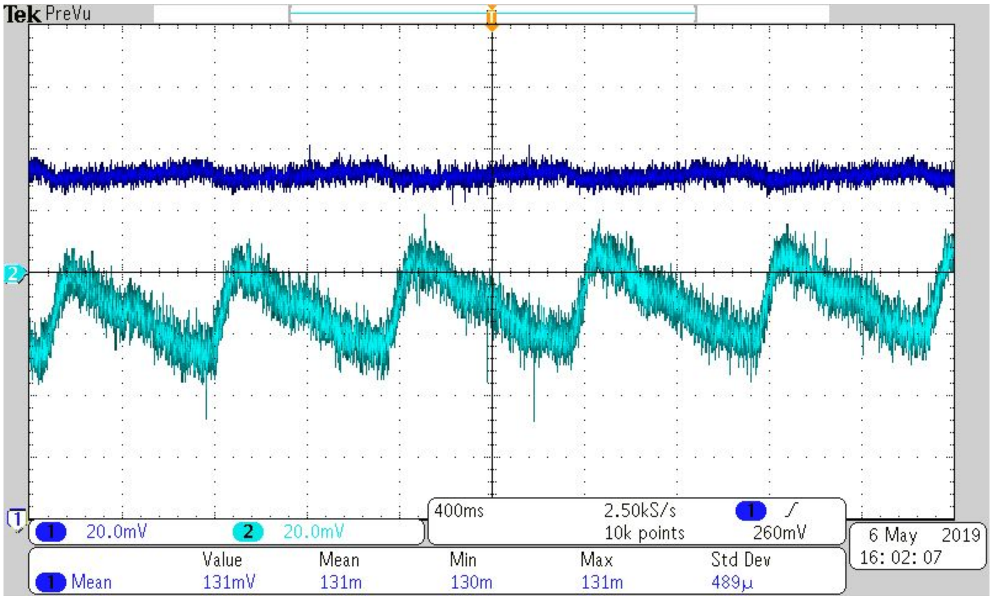
Measuring the input signal time period on the oscilloscope (input heart rate)

Above is the screenshot of the signal from the photodiode before any filters or amplification. Measuring the period of the signal, we have a time frame of 1.412 seconds for 2 beats or a heartbeat of 1.42 Hz.



Unfiltered output in signal 1 and the filtered output in signal 2.

In the above screenshot we measure the output stage of our circuit after our 4th order bandpass filter.



Oscilloscope screenshot showing the raw input signal (signal 1) and the filtered and amplified final output signal (signal 2)

The final signal out was inverted in relation to our input signal due to the inverting gains stage. The output was relatively noisy most likely due to the construction of our circuit being spread out on different bread boards and using longer jumper wires to connect them.

Conclusion

Improvements could have been made for the band-pass filter at the low cut-off frequency. The design asked for a -3dB loss at 0.1 Hz frequency.

Though a signal was received, filtered and amplified, there was still noise from the environment and the circuit itself due to how the final circuit was built. The circuit was built in pieces and wired together, a better alternative would have been to make the circuit all on one bread board and with leads as short as possible. The filter and gain stages both worked well but the resulting waveform was 10x smaller than anticipated.

For construction of the finger apparatus, one issue that lead to a smaller signal was the alignment of the light source and the sensor. The alignment was much more important than anticipated and a future change would be more tightly controlled manufacturing of the actual housing. Any small deflection when drilling the holes for the light and the sensor made a huge difference in signal transmission.

References

The idea for the current source we used was given by Boris, Luis, and Brenan

Professor Lam gave us advice when building our circuit to account for values that weren't matching to those expected from our simulations and datasheets.

Howland current pump
https://www.allaboutcircuits.com/technical-articles/the-howland-current-pump/
LM324 Quad Op-Amp Datasheet
http://www.ti.com/lit/ds/symlink/lm324-n.pdf
NE5534 Op-Amp Datasheet
http://www.ti.com/lit/ds/symlink/ne5534.pdf
LM741 Op-Amp Datasheet
http://www.ti.com/lit/ds/symlink/lm741.pdf
OP906 Photodiode Datasheet
https://datasheet.octopart.com/OP906-TT-datasheet-126867.pdf
L7805ABV 5V linear voltage regulator Datasheet
https://www.st.com/resource/en/datasheet/l78.pdf