ECE 118: Intro to Mechatronics
Lab 1: Signal Conditioning and Filtering
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Overview

This project consisted of two circuits. The first was a track wire detector, designed to use the properties of an inductor to sense whether or not there was current running through a track wire at a distance of up to two inches. The current in the wire induces an oscillating magnetic field around the inductor, which can then be detected as a voltage. This passes into a non-inverting amplifier, injected with a DC signal of 1.65V to prevent clipping that would otherwise be caused by powering the op-amps in this circuit at 0V to 3V. Next, it is passed into a peak detector, and then into a comparator, and finally into a voltage follower, which makes the signal suitable to be read by a microcontroller. An LED indicates whether or not the track wire has been detected.

The other circuit is an infrared beacon detector. It senses 2kHz signals and rejects 1.5 and 2.5 kHz signals. In order to sense the infrared, it uses a phototransistor connected to a transresistive amplifier. Next, it passes into an amplification stage, and from there into a bandpass filter to remove unwanted frequencies.

All of the op-amps in this project are MCP6004s.

Project Design

Part 1: Circuit Module Basics

In this part, the six stages of the track wire detected were constructed and tested individually, using an oscilloscope, a signal generator, and a variable DC power source. We made a track wire by simply running a 25 kHz sine wave signal through a resistor using the signal generator, in lieu of the official track wire that was used to test Part 2.

1.1: Solenoid/Inductor

The first step was to identify the solenoid and test it on its own. When the track wire is brought close, it should induce an oscillating voltage that can be sensed by an oscilloscope. From Fig. 1, the frequency detected by the solenoid was about 25 kHz and the peak to peak amplitude to be 141 mV.

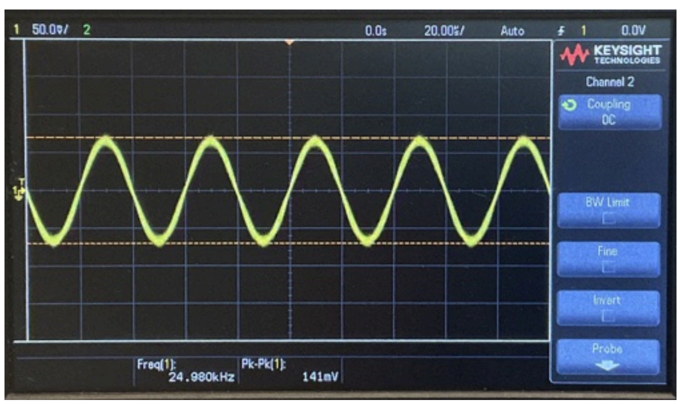

Fig. 1: Voltage induced in the solenoid by a track wire.

1.2: Tank Circuit

Next, the solenoid can be put in parallel with a capacitor and a resistor to create a tank circuit. A tank circuit is an LC oscillator; this one oscillates at a resonant frequency close to 25 kHz (around 27 kHz), so the 25 kHz track wire should cause large oscillations. We observed, in Fig. 2, with a frequency of 24.9 kHz.

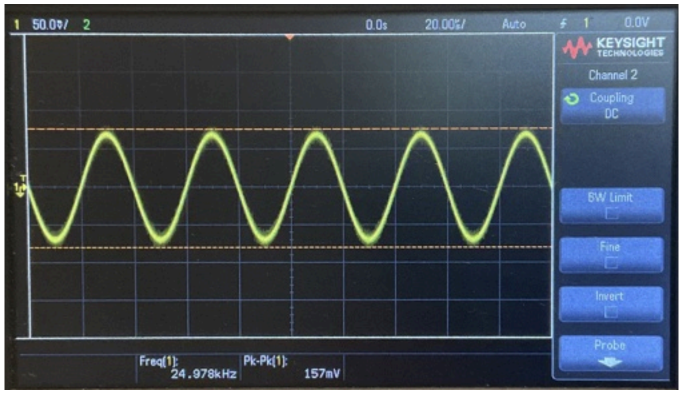

Fig. 2: Tank circuit output.

1.3: Split Rail Buffer

All of the op-amps in these circuits are powered from 0 to 3.3V, due to the thought that this all will eventually need to be connected to—and powered by—a microcontroller. However, the voltage in the track wire goes below zero, and so the signal will be clipped at zero by the amplification stage if nothing is done to mitigate this effect.

In order to prevent that clipping, the amplifier and tank circuit are biased by a DC voltage of 1.65V. This is generated by a split rail buffer. It consists of an operational amplifier and a simple voltage divider.

1.4: Non-Inverting Amplifier

Initially, we built a simple non-inverting amplifier with a gain of 2. Since the transfer function is H(s) = R2/R1+1, which is also the gain, the two resistors simply need to be the same. We chose 10 kΩ resistors for this.

In order to avoid the clipping issue, the 1.65V output of the split rail buffer must become a virtual ground for the non-inverting amplifier. However, the amplifier can still be tested without it, and during this part, we simply ensured that it worked.

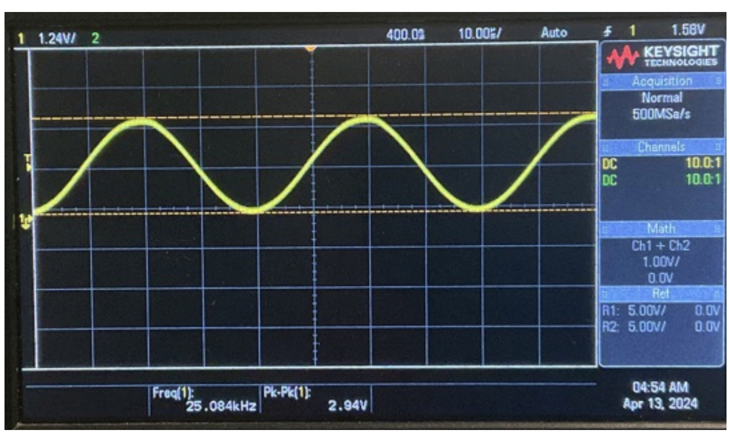

Fig. 3: Non-inverting amplifier with an offset sinusoid created by the waveform generator.

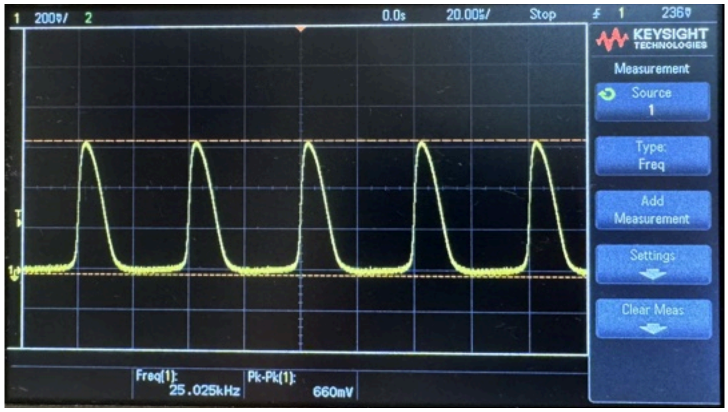

Fig. 4: Non-inverting amplifier with the tank circuit as input, unbiased.

1.5: Peak Detector

A peak detector circuit tracks and maintains the highest value of an input voltage. It operates by using an op-amp to activate a diode, allowing the capacitor to charge when the input exceeds its voltage. Once the input peaks, the capacitor holds this maximum voltage. The diode stops conducting when the input drops, keeping the capacitor isolated and preserving the voltage. A parallel resistor lets the charge gradually leak from the capacitor, setting a time constant that dictates how long the voltage is held before it begins to decay. From Fig. 6, we can see that the voltage is held for the high value of the input voltage and then falls in Fig. 7 when the input voltage is low.

With a capacitor value of 2.2 microfarads and a resistance of 10 kΩ, the time constant is around 22 ms. This is far greater than the period of the input sinusoid (at 25 kHz, this is around 0.04 ms), so the output does not waver in a way that would interfere with our comparator. It is also significantly faster than the specified maximum latency of 200 ms.

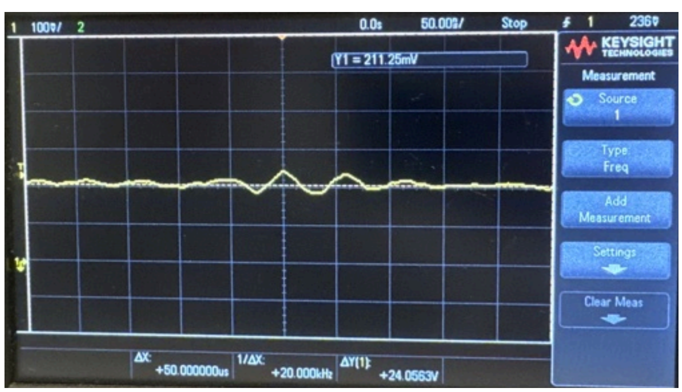

Fig. 6: The peak detector when there is a peak to detect, created by the waveform generator.

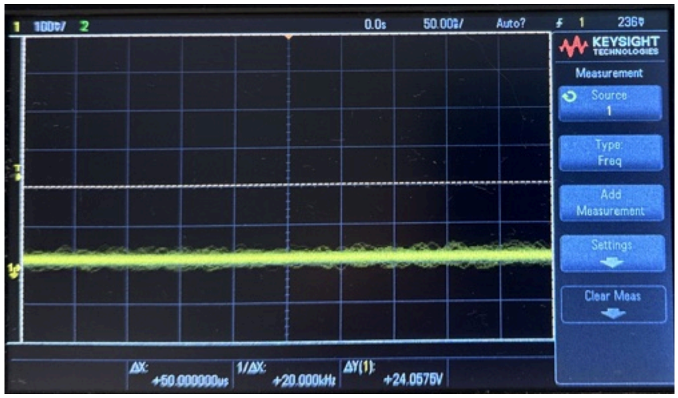

Fig. 7: Peak detector output with nothing to detect.

1.6: Comparator with Hysteresis

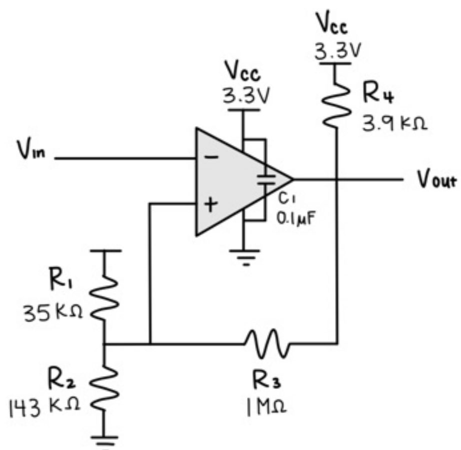

Fig. 8: Comparator with hysteresis.

Using an op-amp configured to be an amplifier, we determined the values of the resistors used based on Appendix A of the lab manual. In this part of the lab, we initially used cutoffs of 1V and 1.8V, as specified by the lab manual. The calculations for those values are as follows:
Given:

1. Lower trip point: $V_{a2} = 1\, V$
2. Upper trip point: $V_{a1} = 1.8\, V$
3. Difference in set points: $\Delta V = 0.8\, V$
4. $R_3 = 1\, M\Omega$
5. $R_4 = 3.9\, k\Omega$
6. $V_{cc} = 3.3\, V$

We calculated:

1. $n = \Delta V/V_{a2} = 0.8V/1V = 0.8$
2. $R_1 = n \times R_3 = 0.8 \times 1M\Omega = 800\ k\Omega$
3. Using the formula: $R_2 = (R_1||R_3)/(V_{cc}/V_{a1} - 1)$, $R_2 = 533.3\ k\Omega$

We implemented these values, and found that the circuit functioned as expected. However, these thresholds did not work with the actual output of the peak detector, as connected in the final circuit. We had to experimentally determine new values, based on the true output of our circuit:

Given:

7. Lower trip point: $V_{a2} = 2.43\ V$
8. Upper trip point: $V_{a1} = 2.54\ V$
9. Difference in set points: $\Delta V = 0.11\ V$
10. $R_3 = 1\ M\Omega$
11. $R_4 = 3.9\ k\Omega$
12. $V_{cc} = 3.3\ V$

We calculated:

4. $n = \Delta V/V_{a2} = 0.11\ V/2.43\ V = 0.0453$
5. $R_1 = n \times R_3 = 0.0453 \times 1M\Omega = 45.3\ k\Omega$
6. Using the formula: $R_2 = (R_1||R_3)/(V_{cc}/V_{a1} - 1)$, $R_2 = 148.2\ k\Omega$

We achieved approximate values for the calculated resistors using what was available, resulting in R_3 = 35 kΩ and R_4 = 143 kΩ. With these values, the comparator functioned as expected, and caused the output to be 0V when the peak detector detected a peak, and 3.3V otherwise.

1.7: LED and Buffer

In the circuit, an LED and buffer stage are used to indicate the output status of the comparator. The LED illuminates when the input to the comparator is low, thanks to a non-inverting operational amplifier set with a gain of one. This buffer stage ensures that the comparator's open collector output can drive the LED without affecting the hysteresis thresholds or overloading a microcontroller's input pins. This arrangement provided clear visual feedback during testing. The circuit was composed of an op-amp, a 47Ω resistor and an LED.

Part 2: Track Wire Detection

In Part 2, we build and test the track wire detection system. This section involved setting up circuits that start with detecting a magnetic field from a track wire. We use an inductor as a sensor to pick up signals from a simulated 25 kHz track wire. This signal is then amplified and processed to create a clear digital output. The individual circuits built and tested in Part 1, were now fed into one another to obtain the final digital signal output.

2.1: Tank Circuit Stage

The first stage involved setting up the LC oscillator along with the solenoid as well as the track wire with an induced frequency of 25 kHz using a waveform generator. Once this stage was verified to have the expected output as in Fig. 2, we moved on to amplifying the signal.

2.2: Amplification Stage

Initially we began with amplifying the signal using an op-amp with a gain of 2 as suggested. We suspected the initial amplification with a gain of 2 would not be enough, so we recalculated the amplification to a gain of 11 and changed the resistor values.

The increase in amplification was to improve the detection of a change in signal in further additions, like the peak detector in the following addition to the circuit. After realizing that the signal was not large enough after the first amplification we added another amplification with a gain of 23. Using the transfer function $H(s) = 1 + \frac{R_2}{R_1}$, which also determines the gain, we chose 10 kΩ and 100 kΩ resistors for a gain of 11 and 10 kΩ and 220 kΩ resistors for a gain of 23.

This would bring our signal up to the desired levels to feed into the next stage. Both amplification stages were biased at 1.65 V using the output of the split rail to have the voltage signal within a useful range.

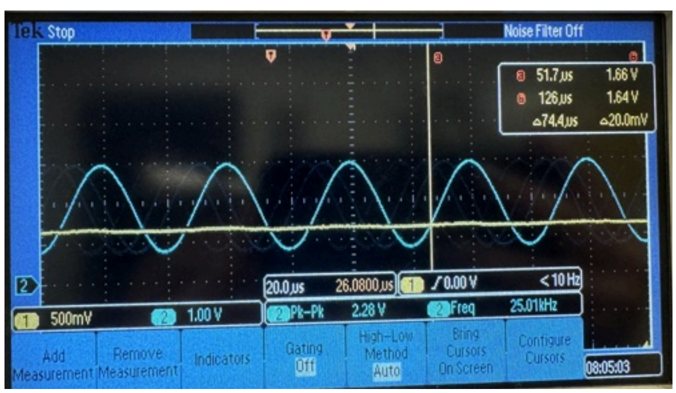

Fig. 9: Amplified output of tank circuit signal.

With the addition of these two amplification stages, the sensor part of this circuit was complete. A full diagram can be found below.

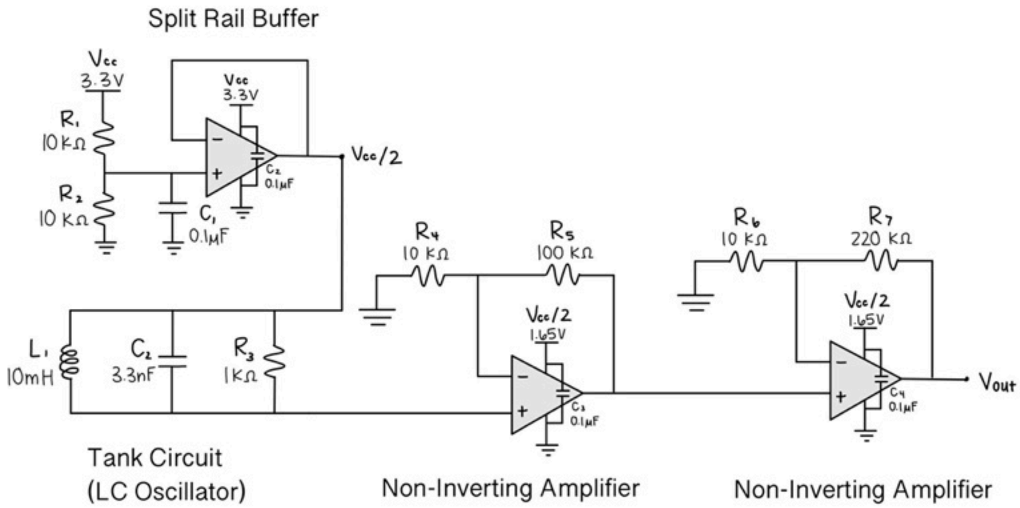

Fig. 10: Amplified sensor signal circuit.

We chose these gains so that the change in the amplitude when the track wire was present would be at least 0.1V, which could then be detected by the comparator. This number was chosen experimentally, after looking at the output of the initial amplifier with a gain of only 2 and thinking about the resistor values we would need for the comparator.

2.3: Peak Detector

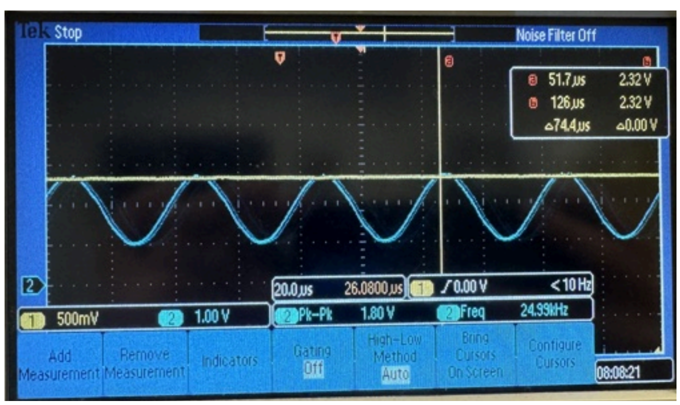

Fig. 11: Peak detector output (in yellow) and input (in blue).

The peak detector functions as described in part 1.5. It required no adjustment from the independently tested circuit developed in part 1. It does not decay significantly between peaks, but the latency is far less than 200ms, as specified.

2.4: Comparator

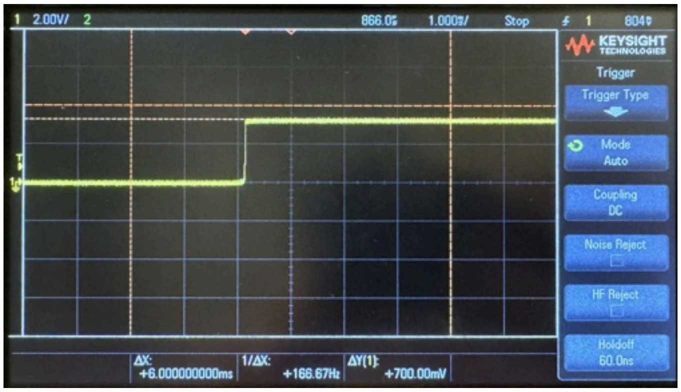

Fig. 12: Comparator output when the track wire turns off.

An op-amp was configured to function effectively as a comparator with a low threshold voltage of 2.43V, resulting in an output of 3.3V, and a high threshold voltage of 2.54V, resulting in an output of 0V. The thresholds were chosen after determining the output of the peak detector. A discussion of the resistor values that achieved these thresholds, as well as a diagram of the comparator, can be found in part 1.6. As before, this comparator is inverting, meaning that the signal is low when the wire is detected.

2.5: LED and Buffer

Finally, the signal was fed into a voltage follower, which has a high output impedance that makes the signal suitable to feed into a microcontroller. An LED was connected to power as in part 1, so that it turns on when the track wire is detected and off otherwise. A picture of the finished circuit, with the LED on to indicate a wire has been detected, as well as the full schematic can be found below.

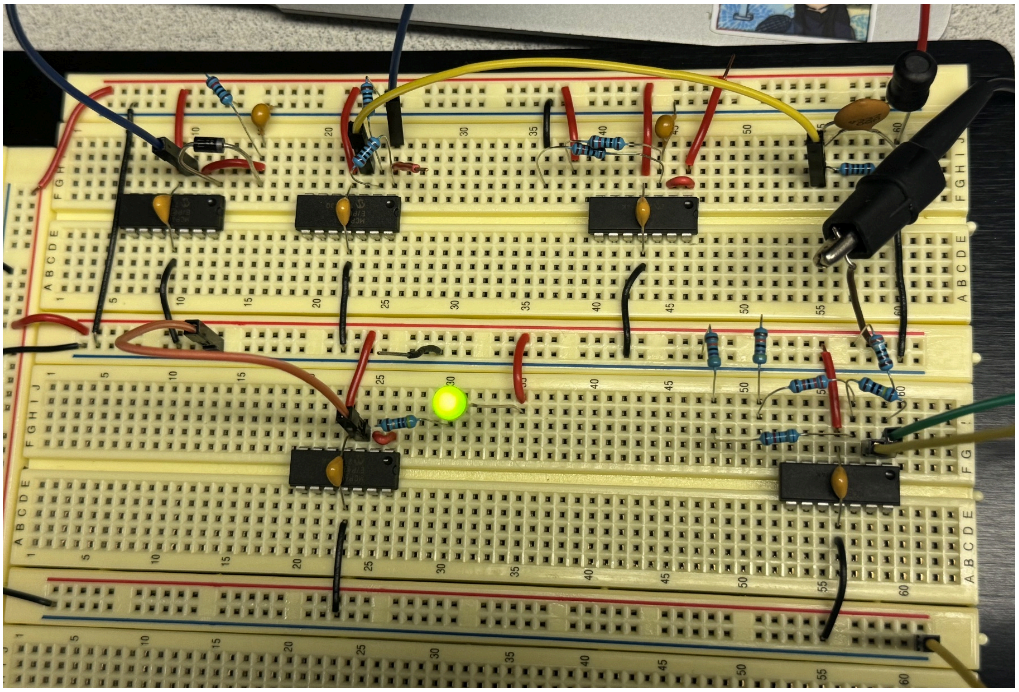

Fig. 13: Full track wire detector circuit with LED output.

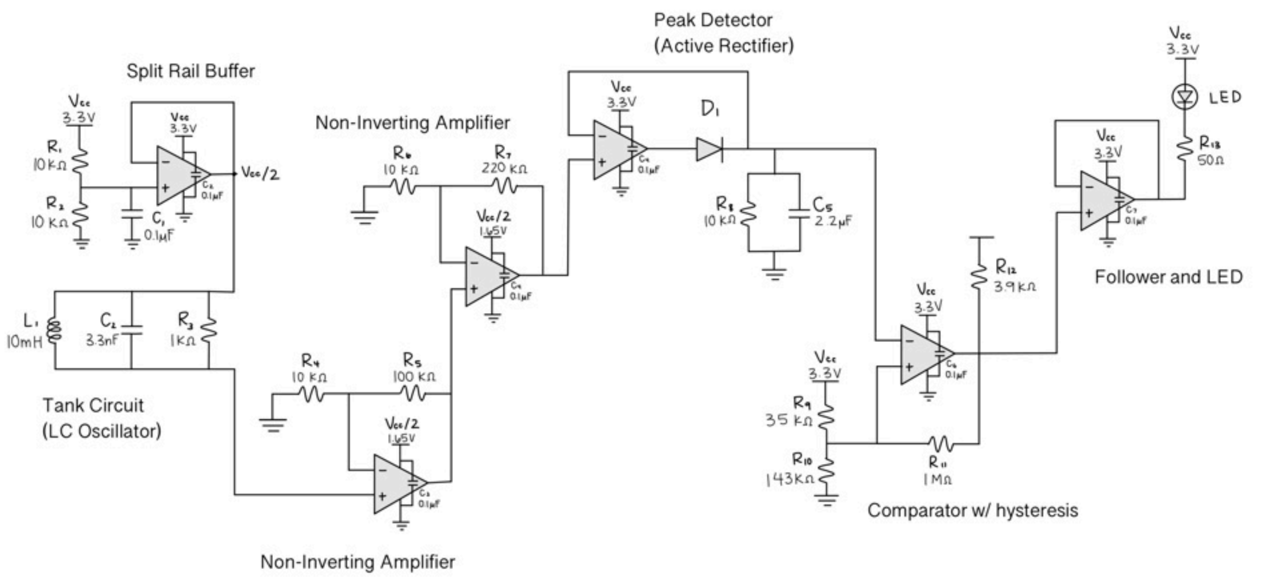

Fig. 14: Full track wire detector schematic with LED output.

Part 3: Phototransistor and Transresistive Amplification

3.1: Sourcing and Sinking Configurations

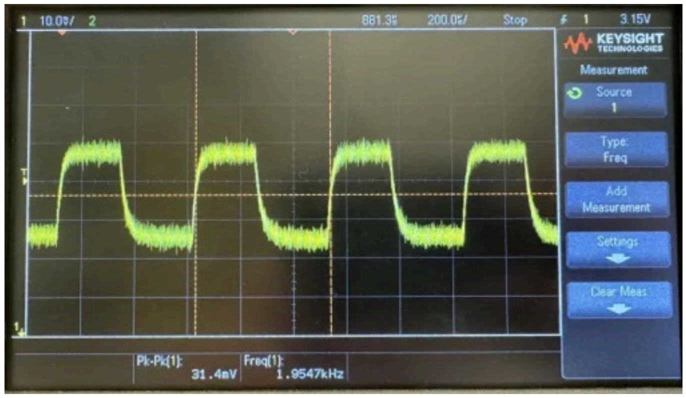

Fig. 15: Sourcing configuration output of phototransistor with 100kΩ.

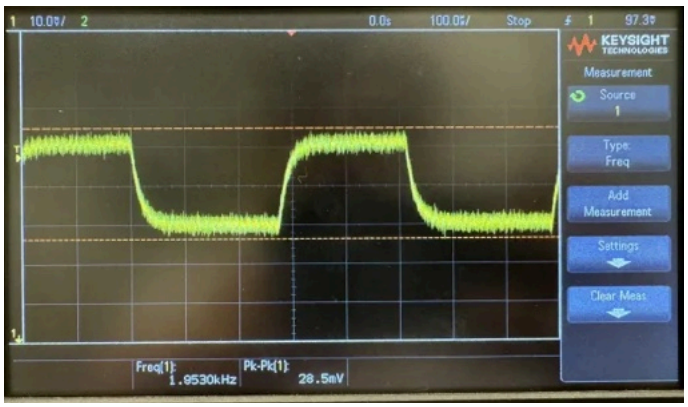

Fig. 16: Sourcing configuration output of phototransistor with 1kΩ.

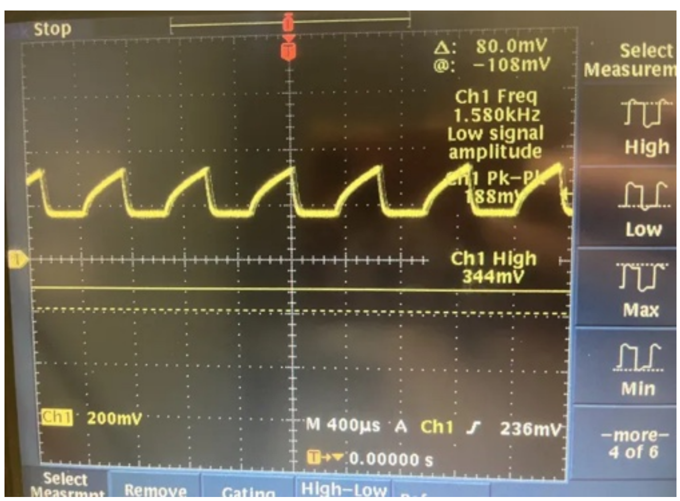

Fig. 17: Sinking configuration output of phototransistor with 100kΩ.

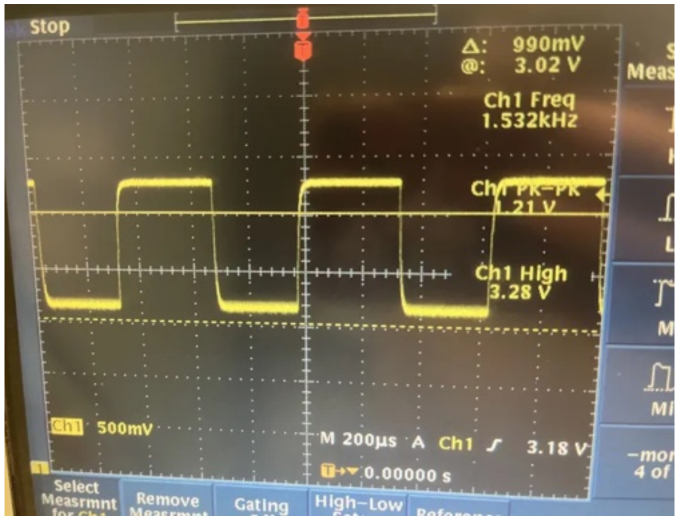

Fig. 18: Sinking configuration output of phototransistor with 1kΩ.

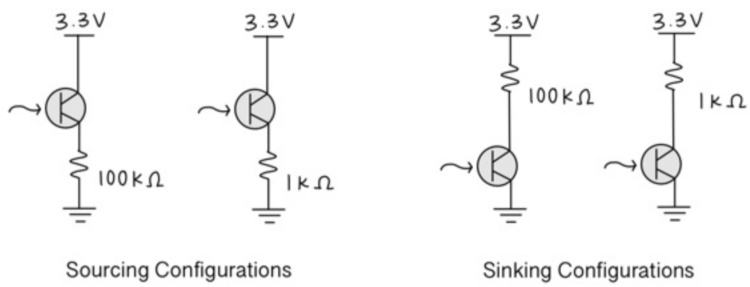

Fig. 19: Sourcing and sinking configuration schematics of phototransistor.

In phototransistor circuits, the impact of changing the load resistor is also influenced by whether the phototransistor is configured in a sourcing or sinking setup. We used the same light intensity for both configurations across both resistors. In a sourcing configuration, the phototransistor allows current to flow when exposed to light, generating a voltage drop across the load resistor connected between the emitter and ground. If the light intensity is constant, using a smaller load resistor results in a smaller voltage drop across the resistor. This can be observed by the peak to peak voltage of 31.4 mV for 100kΩ resistor in Fig. 15 and then dropping to 28.5 mV for 1 kΩ resistor in Fig. 16. The peak to peak voltage was larger for the larger resistor.

In a sinking configuration, a smaller load resistor will result in a greater voltage drop across the resistor, causing the collector voltage to be lower (more towards ground) than it would be with a larger resistor. This results in a higher output voltage change for the same light intensity compared to a larger resistor, which can be observed with a peak to peak voltage of 188 mV for a 100 kΩ resistor in Fig. 17 and 1.21 V for a 1 kΩ resistor in Fig. 18. The peak to peak voltage was larger for a smaller resistor.

3.2: Transresistive Amplifier

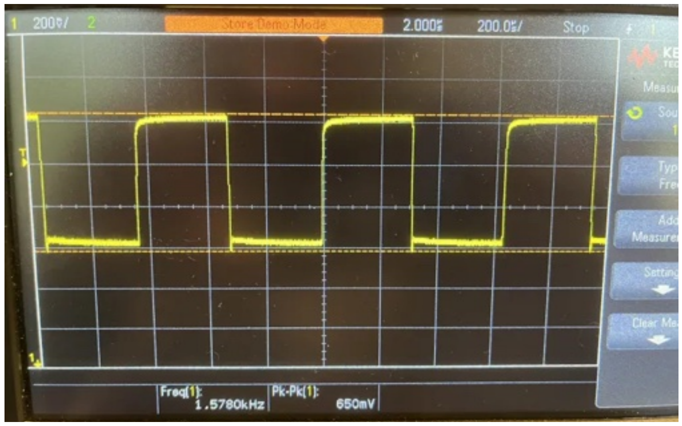

Fig. 20: Transresistive amplifier output.

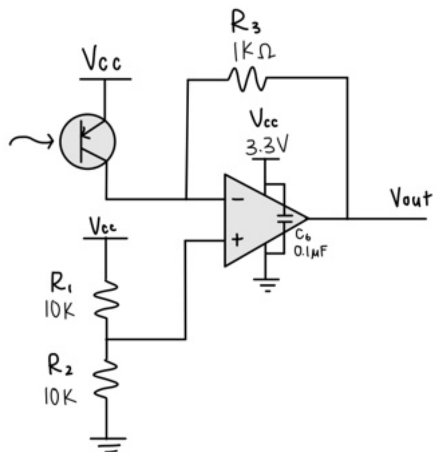

Fig. 21: Full transresistive amplifier schematic.

This transresistive amplifier amplifies the signal for a final peak-to-peak voltage of 650 mV. In the assignment, the specifications indicated that the amplifier ought to have a gain of 1V/mA. The gain is determined by the resistor R_3. Since 1V/1mA = 1V/0.001A = 1000 Ω, this resistor value was chosen to be 1000 Ω.

We observed that this circuit amplified the signal as expected. It also passed the frequencies it was given fairly accurately, with a frequency of 1.5780 kHz reported on the oscilloscope for an input signal of 1.5 kHz.

Part 4: Beacon Detector

This circuit was designed to take the output signal of the transresistive amplifier in the previous section and condition it so that it could be read as a digital signal by a microcontroller, and light an indicator LED. It consisted of two main stages, amplification–to get the change in amplitude to a point that could be reasonably detected by a comparator with feasible cutoffs based on the equipment we had–and a bandpass filter, to filter out noise and other unwanted frequencies.

The bandpass filter is a fourth-order Butterworth, centered around the desired frequency of 2000 Hz, with a passband 300 Hz wide. We experimented with several filters, one of which is still visible on the breadboard, but this is the one which was implemented in the final circuit. A full discussion of the design of this filter and why we chose the ones we did can be found below.

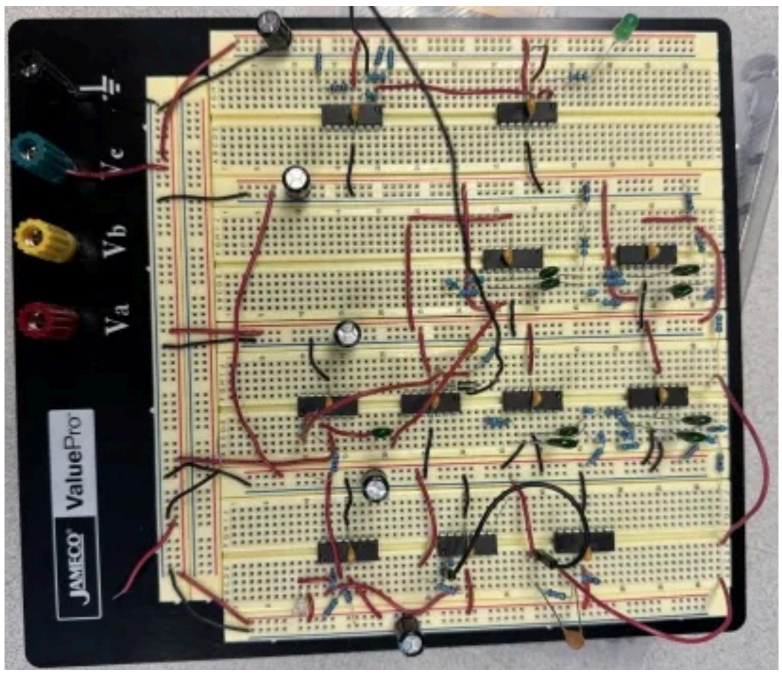

Fig. 21: Full beacon detector circuit with LED output.

This picture shows our finished circuit on the breadboard. The top row is, from left to right, the comparator, the voltage follower, and the indicator LED. The next layer is the bandpass filter, consisting of two stages and two operational amplifiers. The next layer, also from left to right, is an amplifier with a gain of two, a peak detector, and an unused earlier bandpass design, which we kept on the breadboard instead of deconstructing in case it became useful later. Finally, the bottom row is the transresistive amplifier and the first two non-inverting amplifier stages, with a gain of 11 each.

The full schematic with resistor and capacitor values can be found below.

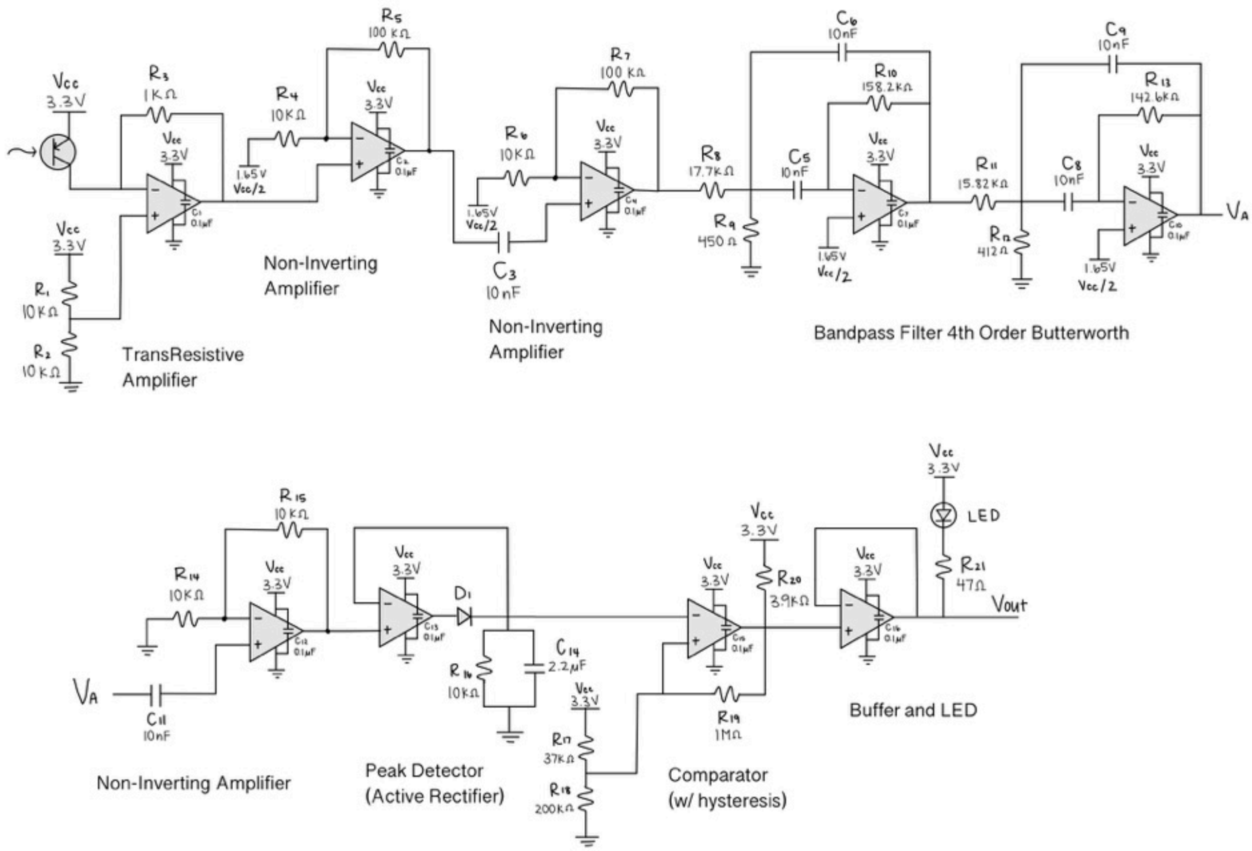

Fig. 22: Full beacon detector schematic with LED output.

The only thing that does not appear on this schematic is the 10 microfarad capacitors we used to connect power and ground. Before adding these, we had some ground loop issues, with internal resonance within the circuit causing a clear 2.2 kHz signal. Adding in these capacitors eliminated the extraneous signal.

4.1: Amplification Stage

The gain values for the amplification stage of this circuit were largely determined experimentally. We knew the signal coming out of the transresistive amplifier and phototransistor circuit would have a peak-to-peak voltage of 0.650V, centered around 1.65V. However, due to the large tolerances (around 20%) on the capacitors, it was difficult to know exactly how much the bandpass filter would attenuate the signal.

We began with two non-inverting amplifiers, each with a gain of 11, achieved with 10kΩ and 100kΩ resistors. This stage came first out of convenience, because it was simpler and easier to test than the bandpass filter. Both these amplifiers were tested independently and together, and they achieved the gains that we expected.

Both were biased at 1.65 V to avoid clipping. In order to recenter the circuit and avoid railing to 3.3V, a 10nF capacitor was inserted between amplifier stages in order to remove the previous bias and re-center the waveform around 0V.

Next, the signal was fed into the bandpass filter. Our final design of this filter also had a gain of 10V/V, or 20dB. However, we discovered that this was still not enough gain to get a decent change in amplitude for the comparator.

After the bandpass filter, we added a third amplification stage. We placed it after the bandpass filter for convenience, in order to keep our wires neater and shorter. This stage was the first place where we truly had to consider the tradeoffs inherent in our choice of amplifiers: two much amplification, and when the beacon was close and emitting 1.5 kHz or 2.5 kHz, the attenuation from the bandpass filter would not be enough, and the circuit would still sense the beacon.

This could be fixed by improving the bandpass filter to make it closer to an ideal brick wall filter, or by making the passband smaller. However, both of those are possible only to a limited degree. In the end, after experimenting with both different gains and different filters, we chose a gain of 2, achieved with two 10kΩ resistors.

All of these amplifiers together–including the amplification from the bandpass filter–provide a gain of 2420 V/V, or 67 dB. The actual gain may be a little less than this, after taking the attenuation from the bandpass filter into account.

4.2: Bandpass Filter Stage

For our filtering stage, we chose a fourth-order Butterworth filter. The topology consists of two Sallen-Key bandpass filters, connected together. The passband is 300 Hz wide, and the center frequency is 2000 Hz, for corner frequencies at 1850 Hz and 2150 Hz.

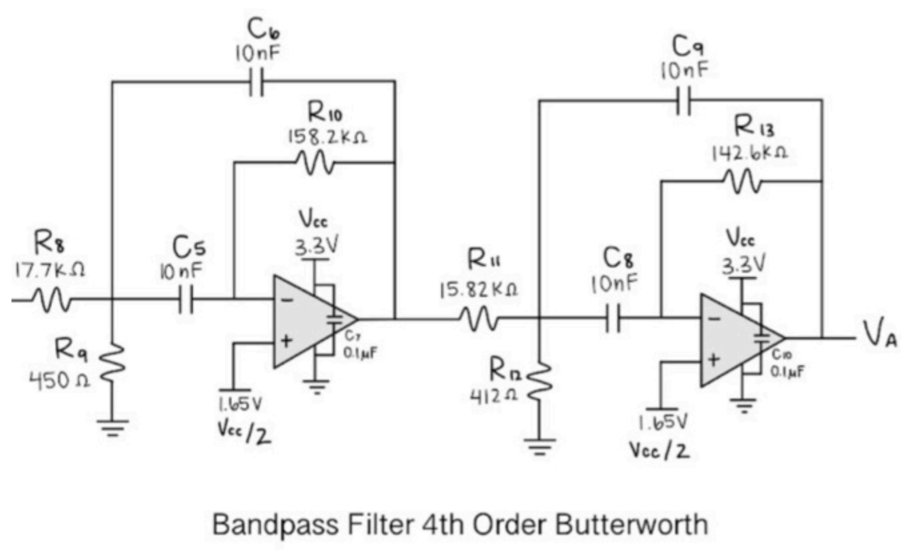

Fig. 23: Bandpass filter stages.

The resistors were chosen to match these values as closely as reasonably possible within 2-3 resistors. The capacitors used were Mylar capacitors, since we suspected them of having better tolerances than the ceramic disk variety.

This filter attenuates frequencies outside its passband at -40 dB and amplifies frequencies inside its passband at 20dB, or 10 V/V. Originally, we designed filters with wider passbands (400-500 Hz), and discovered that they were not enough to meet the specifications. Narrowing the passband further would be another tradeoff, in that the behavior of the circuit would become less predictable due to the capacitor values, and eventually exceed the capabilities of our equipment.

As expected, this circuit attenuates 1.5 kHz and 2.5 kHz frequencies. With the amplification stages, it is sufficient to create a change in amplitude of 0.1V when the correct frequency is detected, at around 1-8 feet.

4.3: Comparator

Finally, the peak detector and the comparator were constructed according to the method in the previous parts. Our peak detector was largely unchanged. The same time constant was more than sufficient to keep the output from oscillating, so the same time constant was used.

The output of the peak detector was used to set the thresholds for the comparator. The same method was used as in part 2. We wrote a MATLAB script to calculate R_1 and R_2, the two resistor values that are used to set the thresholds.

```
%% Comparator design
% R4 and R3 stay constant
R4 = 3900;
R3 = 1000000;

% Set comparator voltage thresholds here
highV = 2.8;
lowV = 2.7;

% Set Vcc
Vcc = 3.3;

% Calculate change and n
change = highV - lowV;
n = change / lowV;

% Calculate R1 and R2
R1 = n*R3
R2 = 1/(1/R1 + 1/R3)/(Vcc/highV - 1)
```

Fig. 24: MATLAB code to generate comparator resistor values.

Based on the peak detector, we set the high threshold at 2.8V and the low threshold at 2.7. The resistor values generated by this script were 37k and 200kΩ, respectively. These could be used with very good accuracy by the resistors in our kit, by using two resistors in series for each value.

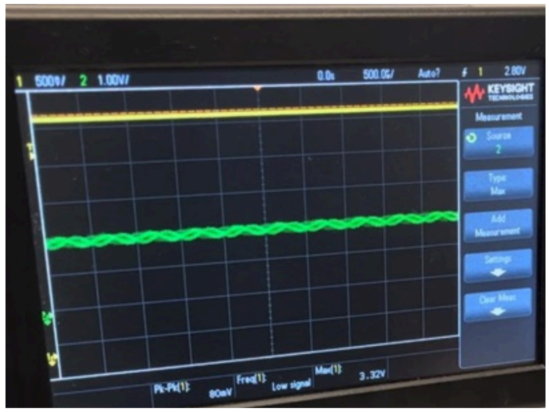

Fig. 25: Oscilloscope traces from the beacon detector, while not detecting a signal. Yellow is the comparator output, green is the input to the peak detector.

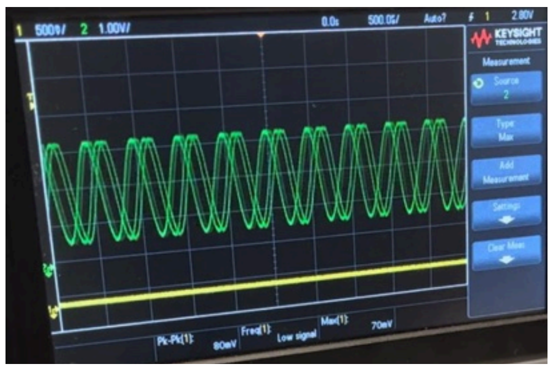

Fig. 26: Oscilloscope traces from the beacon detector, when detecting a 2 kHz signal. Yellow is the comparator output, green is the waveform input to the peak detector.

Conclusion

At the end of this assignment, both circuits met the specifications. The track wire detector detected wires two inches away and with less than 200 ms delay. The beacon detector detected infrared frequencies of 2kHz at 1-6ft, while rejecting other frequencies at around the same distance. However, during the daytime, the beacon detector requires some mechanical shielding from daylight, which otherwise interferes with the signal.