Metal Detector Final Project

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Contents

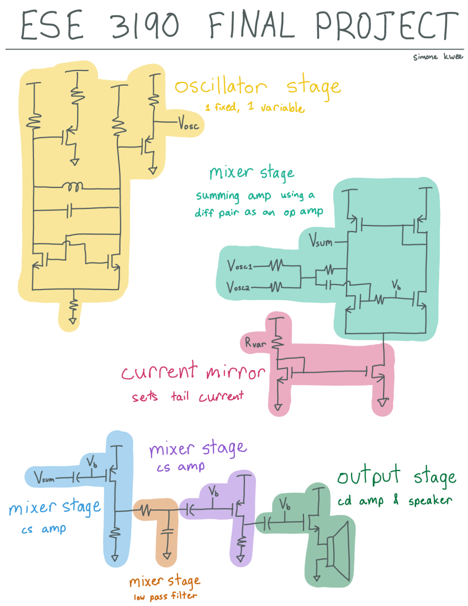

Figure 1: Metal Detector Schematic. There are three main phases: the oscillation stage, the mixer stage, and the output stage.

1 Introduction

The goal of this project was to create a metal detector, which is a device that responds to the presence of metal. Typical applications of metal detectors include uncovering hidden metal objects; for example, metal is hidden underground or within other materials. While some metal detectors use a moving needle to indicate the presence of metal, this project will use a speaker that changes frequency when metal is brought near the device.

2 Design Strategy

The metal detector consists of three main stages: the oscillation stage, the mixer stage, and the output stage. Figure 1 displays the schematic of the mixer

2.1 The Oscillation Stage

This stage of the metal detector makes use of an LC circuit to facilitate an energy exchange that produces oscillations.

Although there are various kinds of electrical oscillators, the oscillator used in this metal detector is related to amplifiers through the use of a feedback loop. The first part of the oscillator consists of the feedback stage - in this section of the oscillator, two CS amplifiers are cascaded and have the outputs tied to the

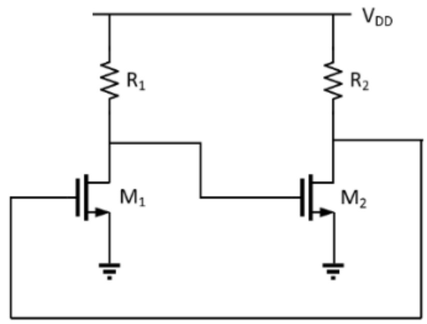

Figure 2: Feedback stage of the oscillator. Consists of two cascaded CS amplifiers with outputs tied to the inputs.

input; the schematic of these amplifiers is provided in Figure 2. This configuration creates the feedback loop, when the output of the inverting amplifier is subtracted from the input, which creates a larger signal. This portion of the system relies on system noise to initialize the sine wave before being mixed with other frequencies.

The oscillator cannot generate sinusoidal functions without a mechanism to set the oscillation frequency. This is where the inductor and capacitor are introduced. When the LC circuit is situated "in between" the two amplifiers (see Figure 3), the signals travel through these components. When the frequencies of the signals are not the fundamental frequency of the LC circuit, the impedance of the LC circuit will attenuate these frequencies; however, when the frequency of the signal is $\omega = \frac{1}{\sqrt{L \cdot C}}$, the circuit will oscillate at its best.

The last portion of the Oscillator is the output stage. In this stage a resistor is added to the sources of the connected CS amplifiers (to serve as a current source). Additionally, CD amplifiers are connected to the outputs of the CS amps to protect the loads of the CS amplifiers. Figure 4 displays the completed oscillator circuit.

There are two oscillators in this device - a fixed oscillator that is driven at 50kHz, and a variable oscillator that changes its output frequency based on the inductance of the metal (which is related to the presence of metal)!

2.2 The Mixer Stage

This stage of the metal detector is a nonlinear circuit that mixes two input frequencies.

To start, the mixer sums up the two sinusoidal inputs; these signals which come from the two oscillators, are input into a summing amplifier, which produces a weighted sum of these frequencies. Figure 5 provides the summing amplifier configuration. Equation 1 provides the values of the output of the

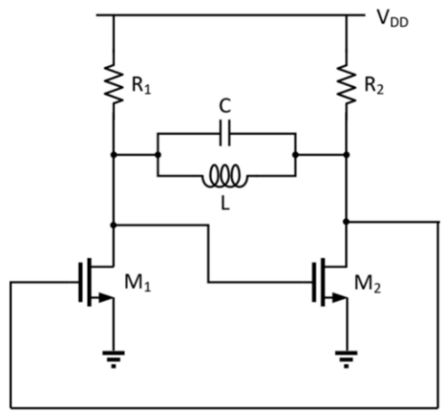

Figure 3: Frequency Definition stage of the oscillator. Consists of an LC circuit in between the two CS amplifiers.

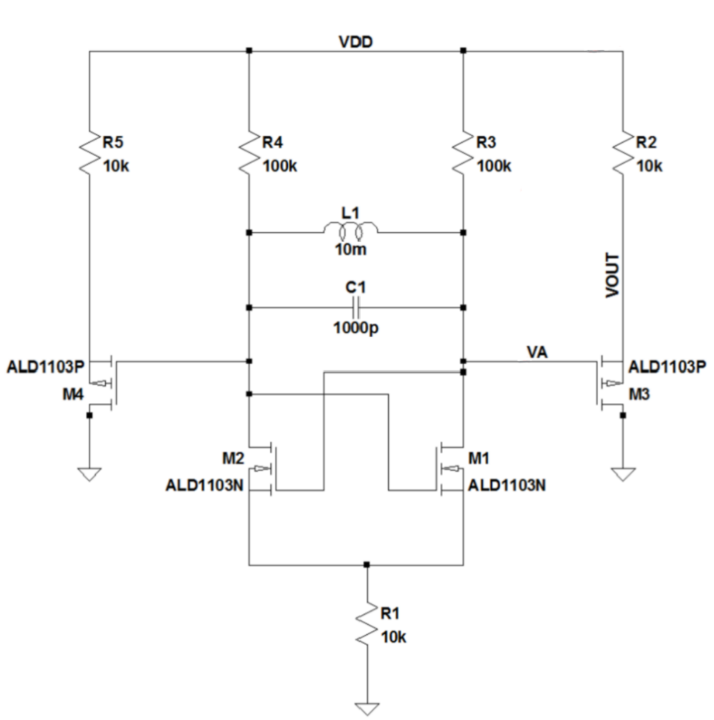

Figure 4: Completed Oscillator Schematic.

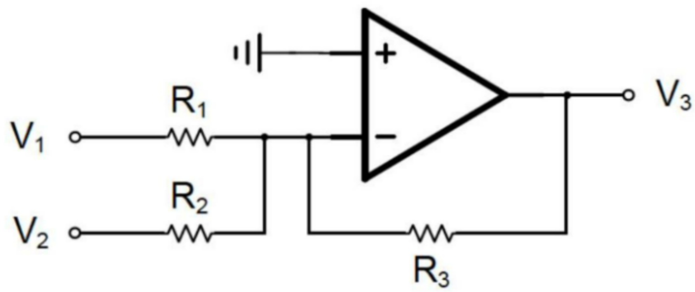

Figure 5: Summing Amplifier step of the Mixer.

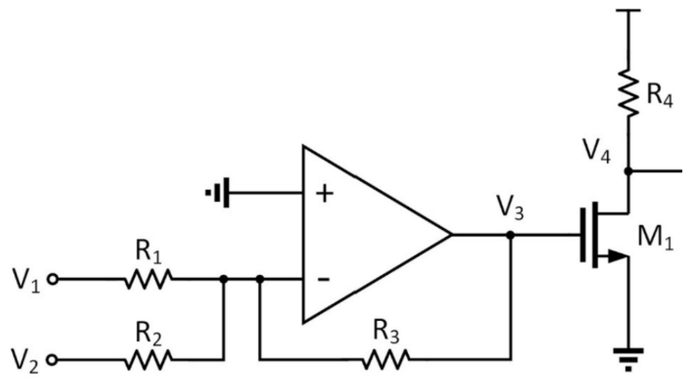

Figure 6: Summing Amplifier Connected to a CS Amplifier. CS Amplifier adds non linearity to the sinusoids.

summing amplifier.

$$V_3 = -R_3(\frac{sin\omega_1 t}{R_1} + \frac{sin\omega_2 t}{R_2}) \tag{1}$$

The non-linearity of this stage comes from the addition of a CS amplifier; the configuration can be seen in Figure 6. This CS amp produces a signal that includes a squared of summed sinusoids. Equation 2 describes the output of the CS Amp portion of the Mixer, where k is $\mu C_{ox}\frac{W}{L}$ and V_{TH} is the threshold voltage.

$$V_4 = V_{DD} - \frac{R_4 k}{2}(-R_3(\frac{sin\omega_1 t}{R_1} + \frac{sin\omega_2 t}{R_2} - V_{TH})^2 \tag{2}$$

The square of the summed sines indicates that the signals are mixed into one sinusoid, which is periodic with respect to the difference between the two original oscillations.

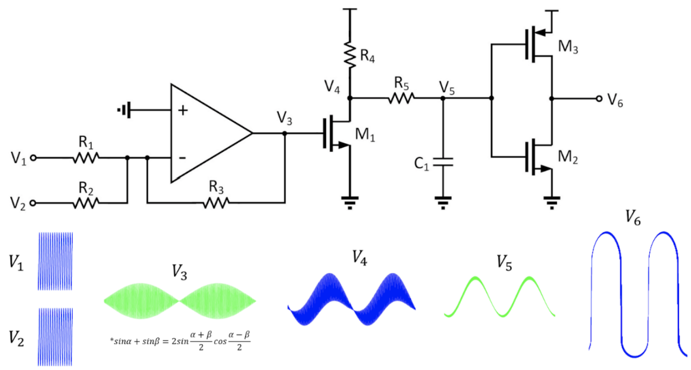

Figure 7: Completed Mixer with Summer, CS Amp 1, Low Pass Filter, and CS Amp 2.

A filter is the next step to the mixer. By adding a low pass filter to the output of the CS Amplifier, and setting the RC and C values such that only the lowest frequency of the mixed signal passed through, it is possible to end with a curve that oscillates only with respect to the difference of the two original oscillation frequencies.

This filtered signal is then passed through a CS amplifier to increase the amplitude of the signal. A completed circuit and output diagram is shown in Figure 7.

2.3 The Output Stage

The output state consists of a CD amplifier. The CD Amp is used to protect the load of the final CS amplifier in the Mixer Stage, to ensure that the 8 Ohm load of the speaker does not tank the CS Amplifier gain. Once the signal is passed through the CD it reaches the speaker, where the difference between the two oscillators can be heard!

3 Hand Calculation

For the detector to output a noticeable signal, the oscillators must produce frequencies with differences within the range of human hearing (around 20Hz to 20kHz). The frequencies used in this oscillator were 50kHz and 48kHz; this is because these values ensure that the detector hits "Goldilocks" spot with respect to metal sensitivity. To ensure that the fixed and variable oscillators output signals of 50 kHz and 48 kHz respectively, the inductor and capacitor values need to be tuned regarding the following equation:

$$\frac{1}{2\pi\sqrt{LC}} = f_{desired} \tag{3}$$

The specific calculations will be provided in the below sections.

Additionally, the value of the low pass filter needs to be tuned to only allow signals of (approximately) 2kHz pass through to the final CS amp. 2kHz is the approximate difference between the two signals generated by the oscillators. The cutoff frequency of the oscillator is determined by the following equation:

$$\frac{1}{2\pi RC} = f_{cutoff} \tag{4}$$

Finally, the resistor for the final CS amp influences the gain of the amplifier, which follows the equations:

$$A_v = g_m \cdot R_D \tag{5}$$

The final CS Amp must have a gain that ensures a detectable output to the speaker. However, because the CS gain is controlled by the load, which can affect the transistor's region of operation, the resistor value must not be too large.

3.1 Fixed Oscillator Calculations

For the fixed oscillator to output a 50kHz wave, using a 10mH inductor, the cap value must follow the following relationship:

$$\frac{1}{2\pi\sqrt{10mC}} = 50kHz \tag{6}$$

$$C = \frac{1}{(2\pi 50kHz)^2 10mH} \tag{7}$$

$$C = 1.01nF \tag{8}$$

3.2 Variable Oscillator Calculations

For the variable oscillator to output a 48kHz wave (when there is no metal present), using a 6mH inductor, the cap value must follow the below relationship:

$$\frac{1}{2\pi\sqrt{10mC}} = 48kHz \tag{9}$$

$$C = \frac{1}{(2\pi 48kHz)^2 10mH} \tag{10}$$

$$C = 1.83nF \tag{11}$$

3.3 Mixer and CS Amplifier Calculations

The cutoff frequency of the low pass filter is $f_{cutoff} = \frac{1}{RC}$; the values chosen for R and C in this circuit are equivalent to 100Ω and 570nF respectively. Taken together, these values yield a cutoff frequency of:

$$\frac{1}{RC} = \frac{1}{100\Omega 570nF} = 2792Hz \tag{12}$$

This value is around 2kHz, and is sufficient for the purposes of the detector (the difference is with the human hearing range).

The resistor for the final CS Amp was set to 8.6kΩ. The transconductance, which is also included in the gain equation is found through the following relation:

$$g_m = \mu_p \cdot C_{ox} \cdot \frac{W}{L}(V_{SG} - |V_{TH}|) \tag{13}$$

For this transistor the important values include: $\mu_p = 550cm^2V^{-1}s^{-1}$, $C_{ox} = 5.75 \cdot 10^{-8}\frac{F}{cm^2}$, $\frac{W}{L} = 100$, $V_{SG} = 3.5$, $V_{TH} = -0.73$

Using the values as stated above, the calculated gain value is 66.3. In reality, CS Amps are not ideal, but the hand calculations ensure that the chosen resistor value will result in amplification of the signal.

4 Simulation Results

The metal detector schematic was simulated in LT Spice to ensure the correctness of the schematic and to ensure reasonable biasing values. The outputs for each stage of the simulation are shown below.

4.1 Oscillator Output

Figure 8 displays the schematic of the Fixed Oscillator. The variable oscillator was the same configuration, however, it uses a different inductor value (which varies in the presence of a metal). The output of the fixed oscillator is shown in Figure 9

4.2 Mixer Output

Figure 10 displays the schematic of the Mixer. The output of the summer, first CS Amp, Filter, and second CS amp are shown in Figure 11.

4.3 Final Output

The final output is the signal that is fed to the speaker; after passing through the second CS, this signal is input to the CD Amp. Figure 12 displays the final output schematic of the Metal Detector; Figure 13 displays the simulated final output.

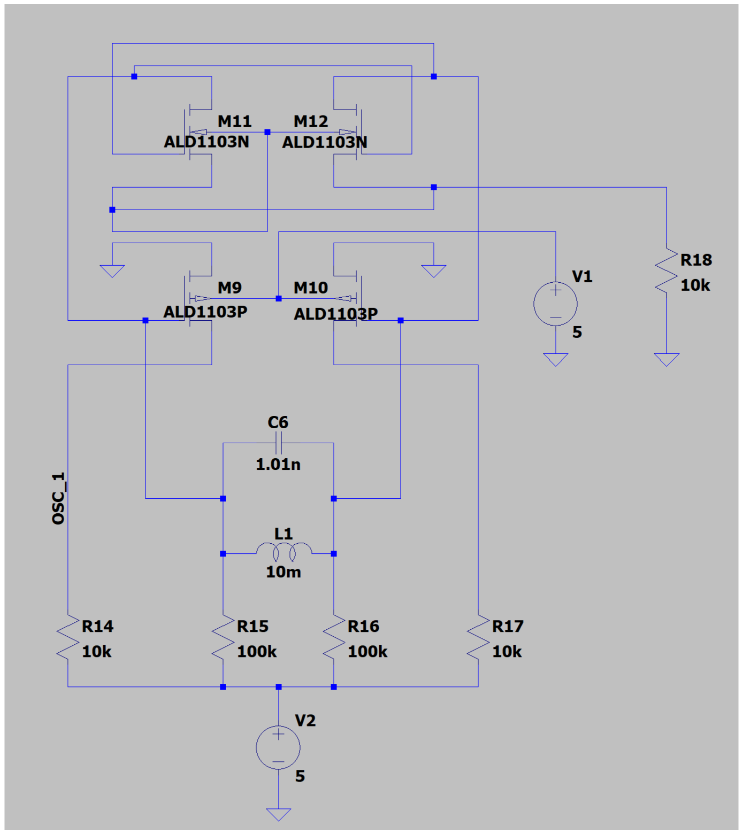

Figure 8: Schematic of the Fixed Oscillator

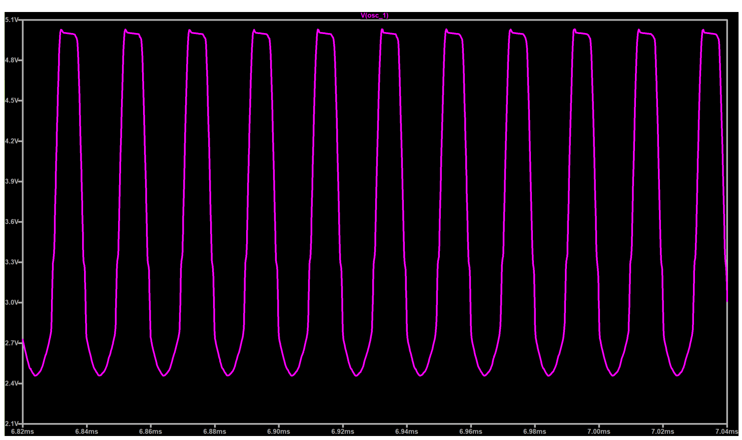

Figure 9: Output of the Fixed Oscillator

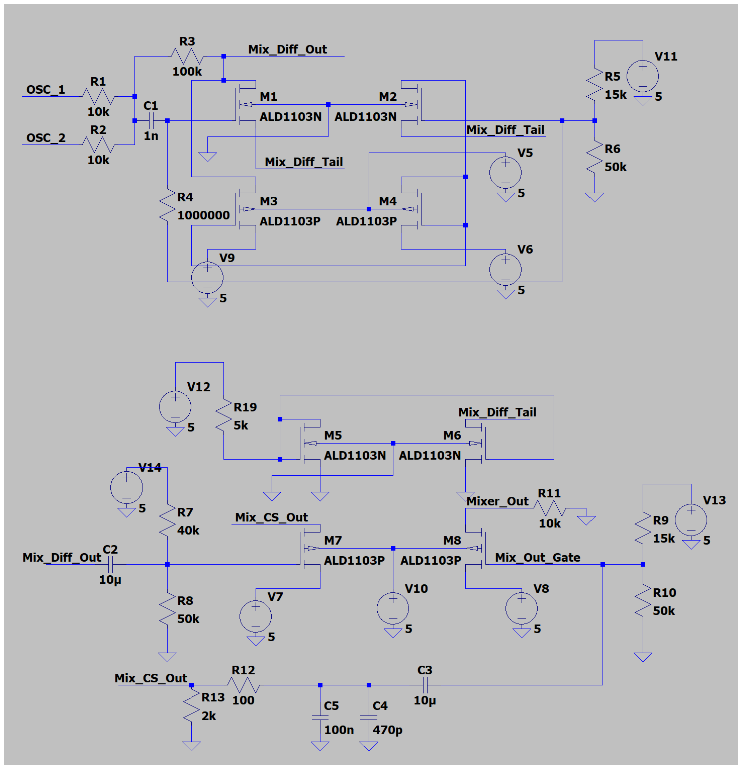

Figure 10: Schematic of the Mixer

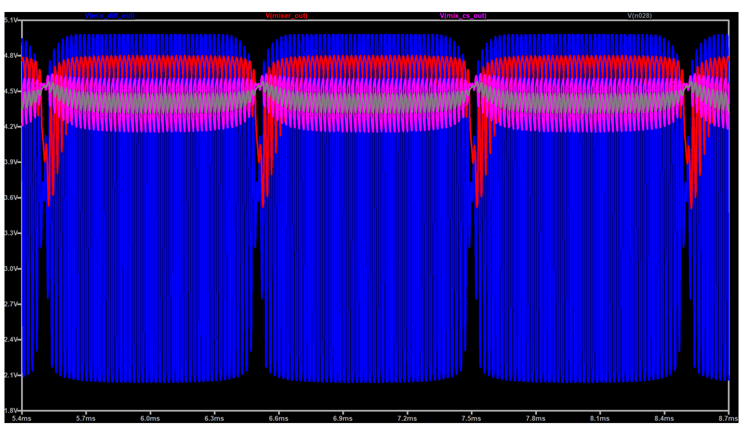

Figure 11: Output of the Mixer. The output of the Summer is the blue trace, the output of the first CS Amp is the pink trace, the output of the Low Pass Filter is the grey trace, and the output of the second CS amp is the red trace.

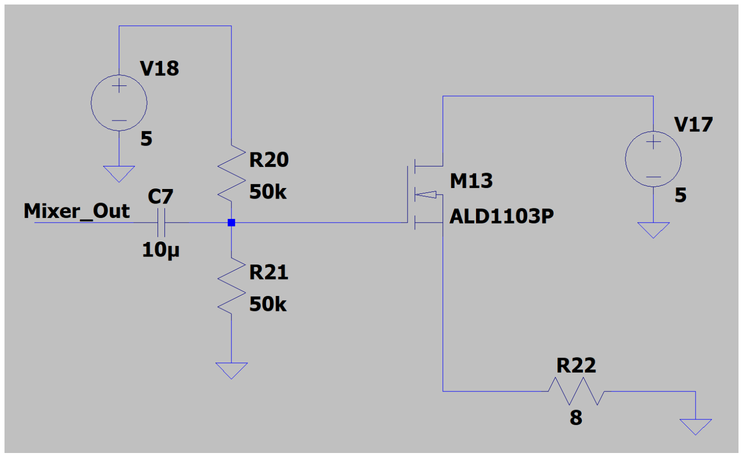

Figure 12: Simulation output circuit.

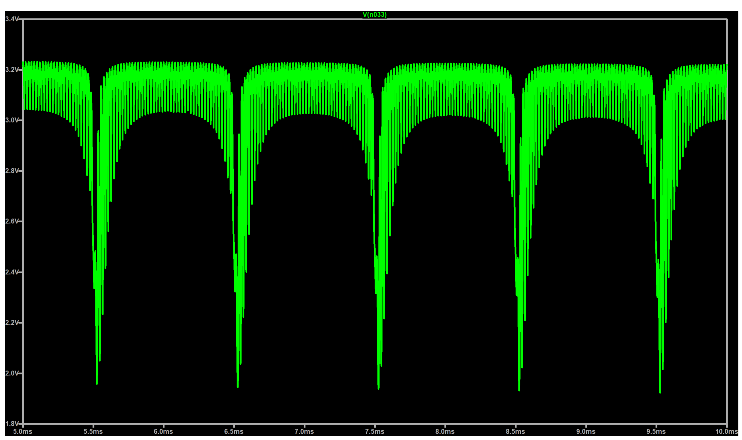

Figure 13: Simulated Final Output (after the CD Amp).

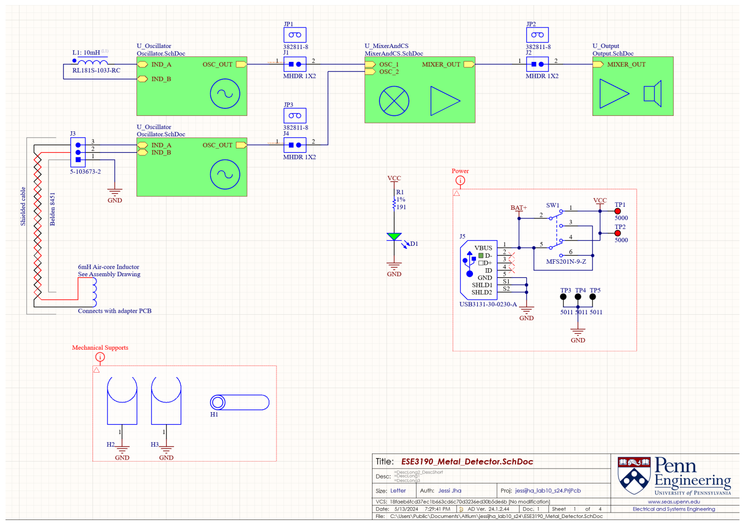

Figure 14: Block diagram of PCB, outlining the various stages of the metal detector.

5 PCB Layout

A labeled block diagram is included in Figure 14. Additionally, Figure 15 displays a labeled version of the metal detector PCB.

6 Measurement Results

This section outlines the experimental procedure regarding the creation and testing of the metal detector. The measured value and oscilloscope screenshots are included.

6.1 Procedure

After the simulation and PCB layout were concluded, it was possible to start the manufacturing of the detector. Beginning the winding the variable inductor, wire was wrapped around a plastic ring to produce an inductor of 6mH. Choosing the correct circuit components and soldering them to the PCB was the next step in Final Project. The PCB was then connected to a PCV pipe and crimped wires, which connected to the inductor.

Once the device was assembled, it was time to test the circuit. The PCB was connected to power; from there, the oscilloscope output and bias values were adjusted in order of stage. The output of the fixed oscilloscope (Figure 16) was measured after choosing the correct capacitor values (which were calculated in Section 3); this same step was repeated for the variable oscillator (Figure 17).

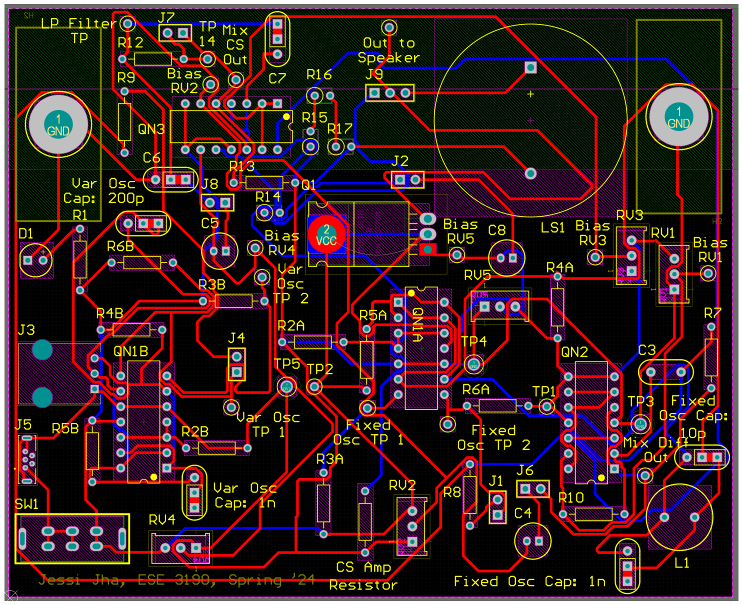

Figure 15: PCB Layout with nodes labeled.

Once the oscillator measurements were concluded, the Mixer and CS stage was connected and bias values of all the transistors were adjusted to match the values in LT Spice. Then the output values were measured for test points 13 the output of the mixer), 15 (the output of the low pass filter), and the output of the CS Amp; these can be seen in Figures 18-20.

The final stage (the CD Stage) was then connected and the output bias at TP 16 was measured (Figure 20). The speaker was then connected to the output, the final step to ensure the device functionality; once the output and speaker were connected a sound played that changed in the presence of metal - the detector worked!

Based on the screenshots of the outputs of each stage, which match the simulated results, it can be concluded that each stage was working properly. Moreover, the detector did meet the design requirement; that is, the frequency of the sound changds when a metal was brought close to the detector.

6.2 Measurements

The oscilloscope screenshots and bias values are attached in this section.

Additionally, the bias values for each of the variable resistors are included in Table 6.2. These values were chosen based on the LT Spice simulation, and ensure that the transistors are operating in saturation.

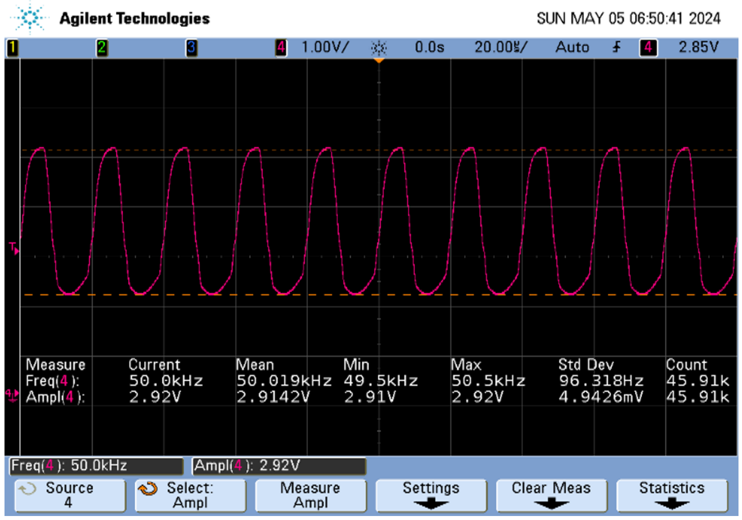

Figure 16: Fixed Oscillator Output with oscillations at 50kHz.

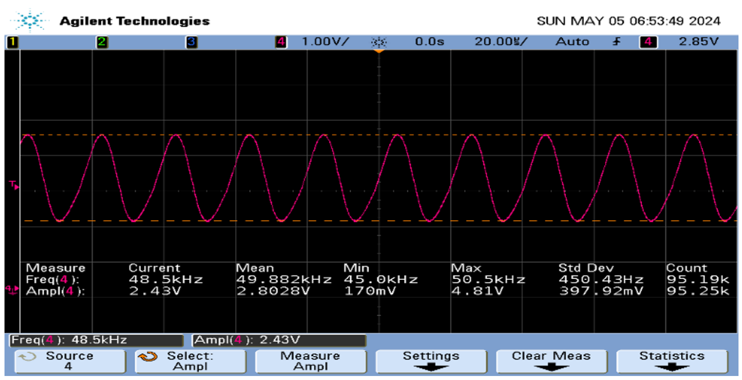

Figure 17: Variable Oscillator Output with oscillations at 48kHz.

Test Point	Bias Values
Bias RV1	3.805 V
Bias RV3	1.163 V
Bias RV2	2.570 V
Bias RV4	3.707 V
Bias RV5	3.132 V

Table 1: Bias Values for Test Points

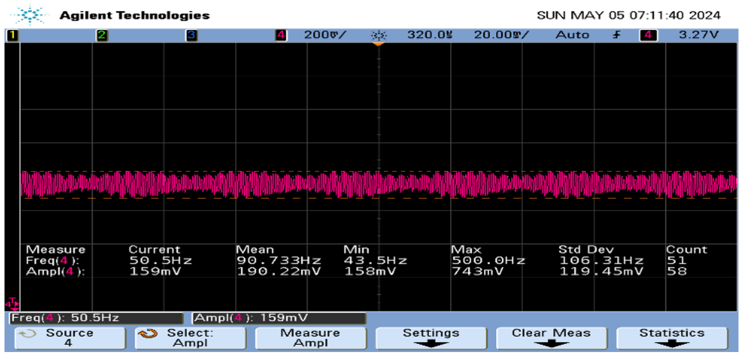

Figure 18: Mixer Output Oscilloscope Measurement; this test point take the form of a sum of sines squared.

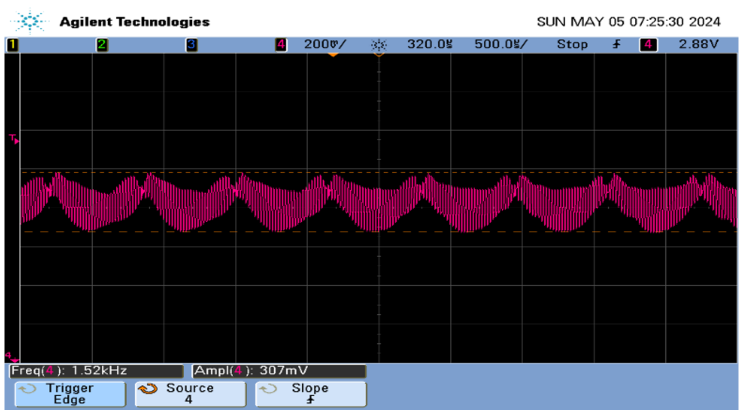

Figure 19: Low Pass Filter Output. This stage filters out signals above 2792 Hz, based on the hand calculations.

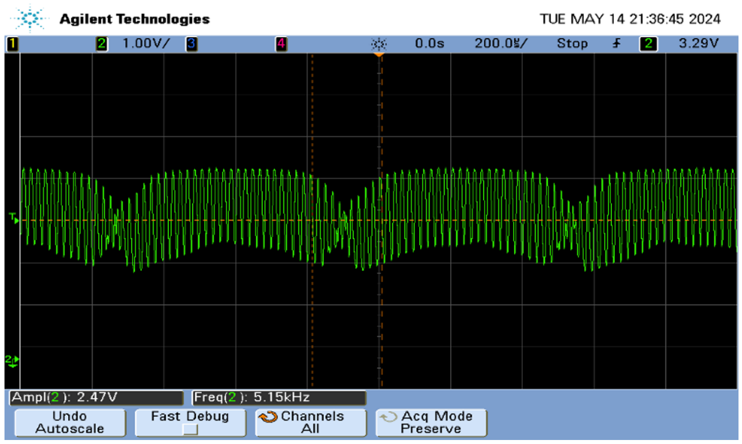

Figure 20: Output of the second CS amp; then gain here is about 8.3, significantly different than the calculated value of gain.

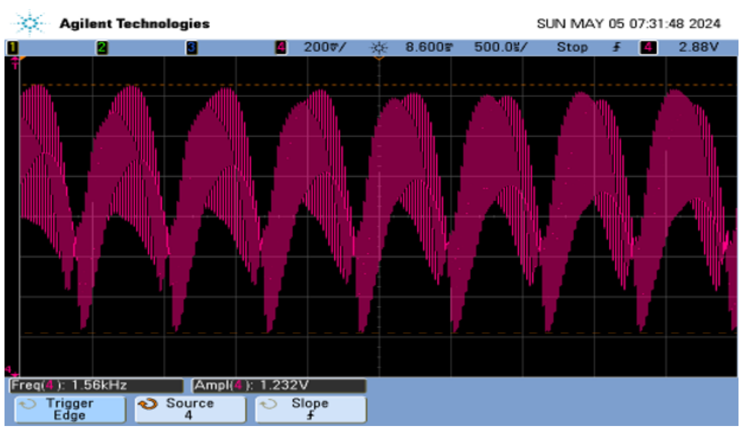

Figure 21: Output to the DC Amp; this is the signal that is played on the speaker. It takes the form of the difference between the initial signals output from the oscilloscopes.

7 Discussion

Due to nonidealities in the transistors, capacitors, resistors, and inductor components, the exact values of the used in the oscillators were slightly different from those used on the actual PCB.

The calculated cap value for the fixed oscillators was 1.01 nF while the real value used was 1.072 nF (basically the same as calculated)!.

The calculated cap value for the variable oscillators was 1.87 nF while the real value used was 1.526 nF.

The values of the calculated and real filter caps were the same, which seemed to work well in this circuit. This was because the exact frequency of the output varied based on the presence of the metal, so as long as the cutoff frequency was larger than the maximum change value of the difference in oscillator frequencies yet still close to the range of differences, the filter would do its job correctly.

Perhaps the most notable difference between the hand calculations and the measured values comes from the CS Amp gain. The calculated CS Amp gain was 66.3 whereas the measured gain was 8.3. In the gain calculations, second-order effects were ignored; thus the model used to determine gain was not fully representative of the actual behavior of a CS amp. Moreover, the components used were not ideal, leading to discrepancies between the calculated and measured values.

8 Conclusion

Overall, this project was interesting! It synthesized a variety of concepts taught in 3190 lectures, including current mirrors, CS Amps, filters, and CD Amps. The project also elaborated on concepts taught in labs, including oscillation circuits (which are used in a variety of applications and devices, like waveform generators) and summing amplifiers. It was also enjoyable to work on a final project that resulted in a useful device; this metal detector could have potential applications in the future.

In comparison to other labs, the project simulation phase was more challenging; it included more stages than other labs, and the values of the caps, resistors, and inductors in this circuit were largely chosen by students. Additionally, the assembly phase (with soldering and crimping) was more involved than typical labs. That being said, once the device was assembled, it was easier to test the functionality of the circuit; having the simulation and Altium schematic ensured minimal errors in the assembly phase.

One way this device could be improved is by testing different values of oscillation outputs coming from the oscillation phase; perhaps tuning the difference between these signals would create a more sensitive device. Additionally, perhaps using a band-pass filter as opposed to a low-pass filter would have produced a cleaner output sent to the speaker.

However, overall, the device did meet design specifications, and had good functionality; it was a successful metal detector!