Final Project Report: Metal Detector

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ESE 3190: Fundamentals of Solid State Circuits

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Introduction

In this project, a metal detector was designed, simulated, soldered, constructed, and measured. This project was a culmination of many units that have been worked through this semester. It includes oscillators, mixers, and multiple amplifiers, such as common source and common drain.

Metal detectors are very common devices today, and the intuition behind them is quite intriguing. It works by taking in two frequencies generated by oscillators, feeding them into a mixer which outputs the difference between them, which is then amplified and buffered into a speaker. Metal detectors are often constructed using a handheld unit with a sensor probe that can be swept over the ground or other objects, which in this case is a large inductor. When metal is placed underneath the large inductor, it creates an eddy current, which opposes the alternating current in the inductor, lowering the inductance and changing the frequency. This change in frequency can then be recorded and sent to the speaker, indicating metal has been found!

This lab report includes a hand calculation section that contains all relevant equations used for this report, a simulation section in which LTSpice was used to tweak parameters, a PCB layout section that details the PCB design that was eventually soldered, and a measurement section in which all stages of the metal detector were verified and discussed.

Design Strategy

Four main stages must be explained: the Oscillator Stage, the Mixer Stage, the Amplifiers (CS Amplifier), and the Driver (CD Amplifier).

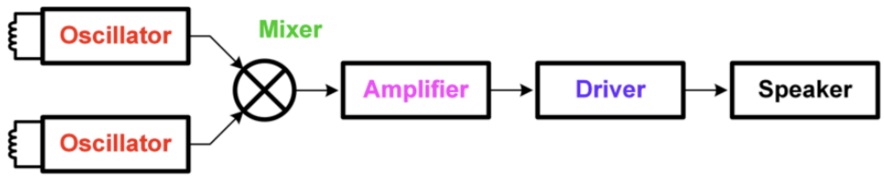

Diagram 1: Metal Detector Stages (From Background Document)

First, the Oscillator stage is made up of two LC Oscillators. In practical applications, carrying a function generator is neither feasible nor efficient. Therefore, using Oscillators is a perfect solution. Electrical oscillators work on the principle of the exchange of energy between the inductor and the capacitor. When a capacitor is attached solely to an inductor, the charges on the two plates of the capacitor surge through the inductor and charge it up, essentially storing energy in its magnetic field. Once the capacitor has fully discharged, the inductor then begins to discharge, which charges up the capacitor. Then, when one plots the voltage across the capacitor, an oscillation has formed.

In the design, two oscillators are used that oscillate at slightly different frequencies (50 kHz and 53 kHz), around 2- 3 kHz apart. One of these oscillators is constant and its frequency does not change, but the other one, positioned at the end of the pole, is a variable oscillator, meaning the frequency can change based on whether metal is near it. The idea behind this is that the alternating current through the variable inductor will generate an alternating magnetic field, which is then interfered with (an eddy current is produced) when a piece of metal is placed near. Lenz's law states that this eddy current will reduce the alternating current going through the inductor, leading to an effective decrease in inductance. Based on the inverse relationship given by the frequency oscillator equation $1/2\pi\sqrt{LC}$, the decrease in inductance will *raise* the output frequency.

These two oscillations feed into the next stage: the mixer stage. The mixer has three components: A summing amplifier that uses a differential pair setup as the OpAmp (and a current mirror as the tail current), two CS Amplifiers, and a low-pass filter.

First, the summing amplifier is used to obtain frequencies $|f_1 + f_2|$ and $|f_1 - f_2|$ where f_1 and f_2 are input frequencies to the amplifier. The output of the summing amplifier signal will look like a modulated sine wave centered at (ω1+ω2 / 2) with an envelope at (ω1 - ω2 / 2). Then this output summed signal will be cascaded into the first CS amplifier, which adds non-linearity. The signal will be amplified here, and then fed into a low-pass filter so that the high-frequency components of the mixer (ω1+ω2, ω1, and ω2) are attenuated and only the difference frequency is outputted, which is around 2 kHz (which fits inside the human frequency hearing range).

This now 2-3 kHz signal is fed into a CS amplifier once again to raise its amplitude (which makes it louder in the speaker) and is then fed into a Common Drain amplifier. This is the Driver stage seen in diagram 1. CS Amplifiers have notoriously high output resistance, but if cascaded with a common drain amplifier, which acts as a buffer, the output resistance is low and the gain is almost entirely maintained. This means that the output can be safely fed into the 8-ohm speaker without losing all the gain, which then plays the audible differential frequency.

With the two base frequencies (which are around 50 kHz and 53 kHz), a 3 kHz signal will be heard out of the speaker. Then, when metal is placed near the variable inductor, as discussed, the frequency will grow, meaning the difference is bigger and becomes around 5kHz, which is a higher-pitched noise, indicating metal is near!

Hand Calculation

To ensure that theoretical predictions line up with actual values, hand calculations will be done for each section. First, the frequency produced by an oscillator is dependent on its inductance and capacitance values.

$$f = 1/2\pi\sqrt{LC}$$

Equation 1: Frequency of an LC Oscillator

In the actual metal detector, after some changes from the prelab, Oscillator A used L = 10 mH and C = 1nF. Plugging into the equation gives: $1/2\pi\sqrt{(10 * 10^{-3})(1 * 10^{-9})}$ = **50.3 kHz**. Similarly, this equation can be used to find the base frequency for the variable oscillator (Oscillator B). Here, L = 9.8mH and C = 900pF. (9.8 mH Inductor was wound as for the variable inductor). Plugging into the equation gives: $1/2\pi\sqrt{(9.8 * 10^{-3})(900 * 10^{-12})}$ = **53.6 kHz**.

Next, the chosen bias points suggest that all MOSFETs operated in the saturation region throughout the circuit's operation. For many of the drains and sources of the MOSFETs, the voltages could not be directly measured, but the relative differences between gate and source voltages were selected to ensure saturation based on the threshold voltage of the devices. Furthermore, all outputs displayed no clipping of the waveform,s which indicates that the transistors were not entering the triode region. All of the chosen bias points were as follows: Rv1 = 2.5V, Rv2 = 3.0V, Rv3 = 4.3V, Rv4 = 3.7V, and Rv5 = 2.8V. According to the saturation condition $|V_{DS}| > |V_{GS} - V_{TH}|$, each qualitatively stayed in saturation.

Next, the low pass filter can be verified that it doesn't cut off frequencies below 5 kHz but cuts off frequencies over 45 kHz, which is the desired behavior because it will filter out the higher frequencies of the mixer output. RC low-pass filters give the cutoff frequency in the form of this equation:

$$f_c = 1/2\pi RC$$

Equation 3: RC Low Pass Filter Cutoff Frequency

In the metal detector, a resistance of 100 Ohm and a Capacitance of 50nF were used, which results in $f_c = 1/2\pi(100)(50 * 10^{-9})$ = **31.8kHz.**

Lastly, R_{11} was chosen for the Common Source Amplifier at the Mixer Output Stage. Gain can be calculated for a CS Amplifier as follows

$$A_V = -R_D g_m$$

Equation 4: CS Amplifier Small Signal Voltage Gain

R_D was chosen to be 1k Ohm. The transconductance, also known as g_m, can be calculated as follows:

$$g_m = \mu C_{ox}\frac{W}{L}(V_{GS} - V_{TH}) \qquad (1)$$

Transconductance in Saturation

In the ALD1103 models used for a PMOS (which is what is used for the CS Amplifier in this case), $\mu = 550cm^2/V*s$, $Cox = 5.75*10^{-4}\ F/cm^2$, and W/L = 100. The gate voltage of the PMOS is Rv5 = 2.8V, the threshold voltage is -0.73V, and the source is at $V_{DD,}$ which is 5V. Thus, the g_m can be calculated as

$$g_m = (550)(5.75 * 10^{-4})(100)(|2.8 - 5 - (-0.73)|) = \mathbf{46.5mA/V}$$

Then, with this g_m value, the final gain of this stage can be calculated.

$$A_V = -(1000)(46.5 * 10^{-3}) = 46.5$$

Now, each stage has been verified with the chosen values, and a summary can be seen below.

Component	Value
Oscillator A Frequency	50.3kHz
Oscillator B Frequency (Base)	53.6kHz
RC Low Pass Cutoff Frequency	31.8kHz
Gain of Mixer Output CS Amp	46.5

Table 1: Summary Of Hand Calculations

Simulation Results

To verify the design, the entire schematic was constructed using LTSpice. Values were tweaked to ensure all stages worked. Two simulations were run for the Oscillator, Mixer, and Final Output stages, with two different inductance values, to see how the “metal” would eventually affect the oscilloscope output.

Here is the full LTSpice Schematic.

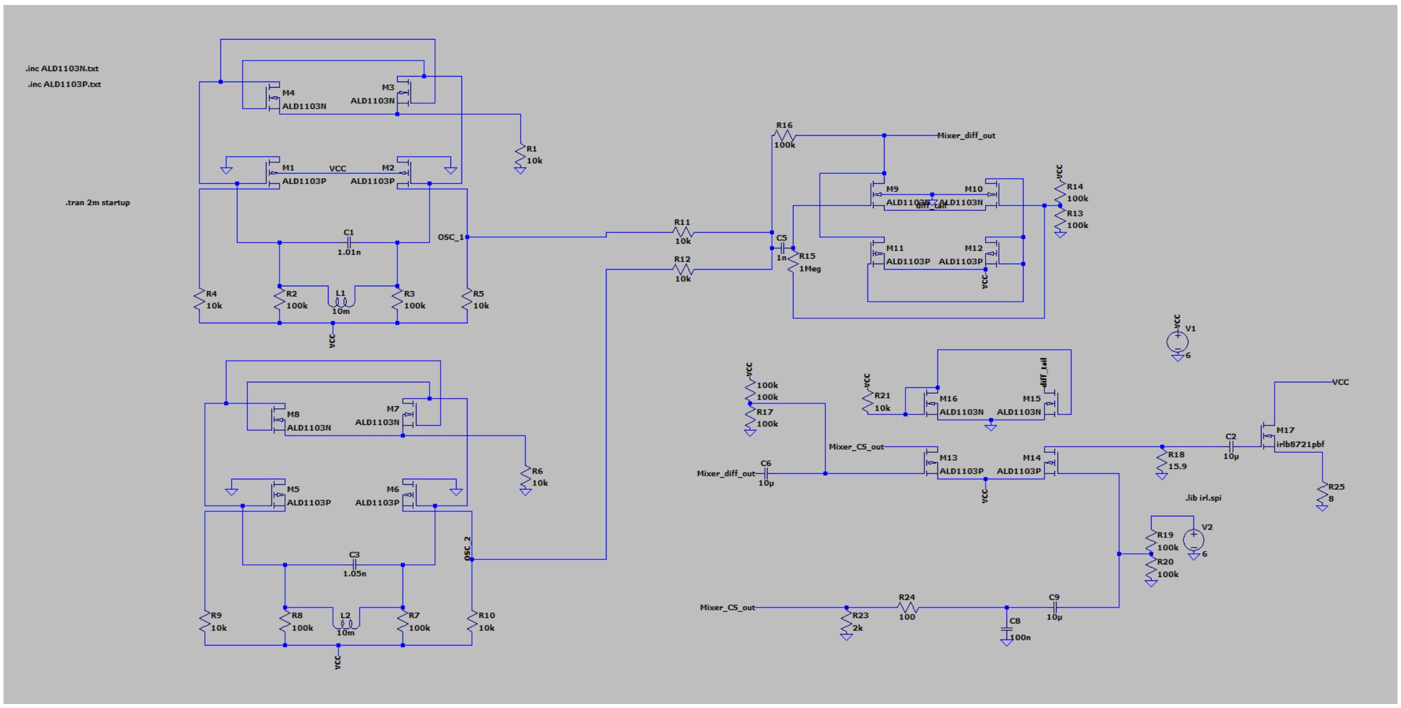

Figure 1: Full Metal Detector Schematic

For the rest of the simulations, the inductance of Oscillator B was altered between 10.0 mH and 10.5 mH (a 5% increase) to emulate metal being near it (where the lower inductance is the metal addition because it lowers L_{eff})

The first stage is the Oscillator stage. Here are the outputs of A and B together.

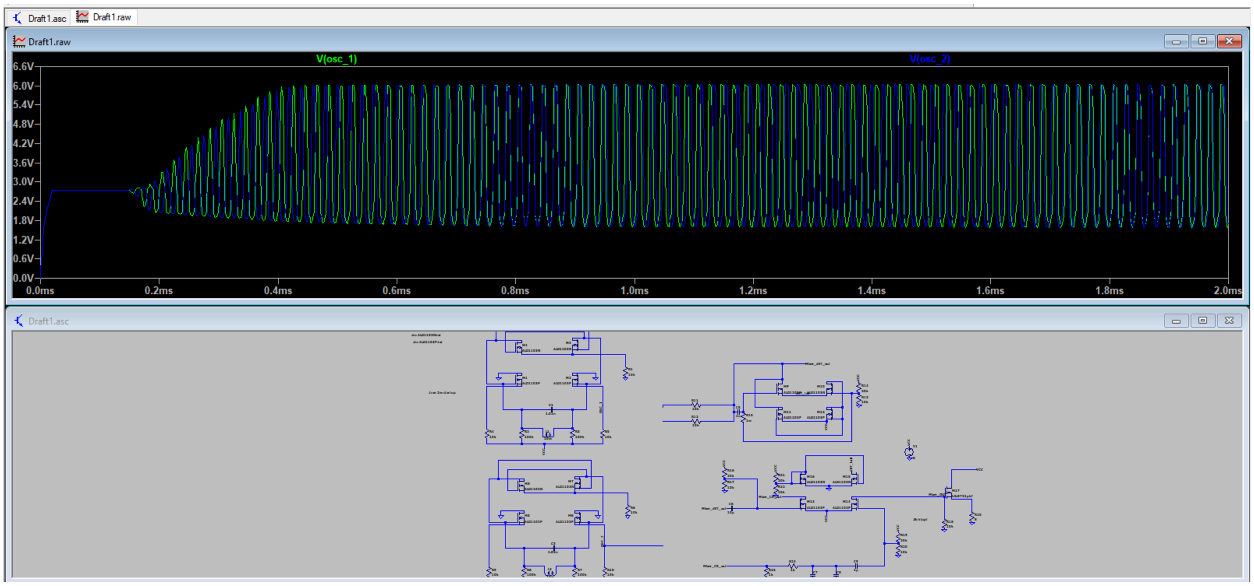

Figure 2. Oscillator A and B Outputs

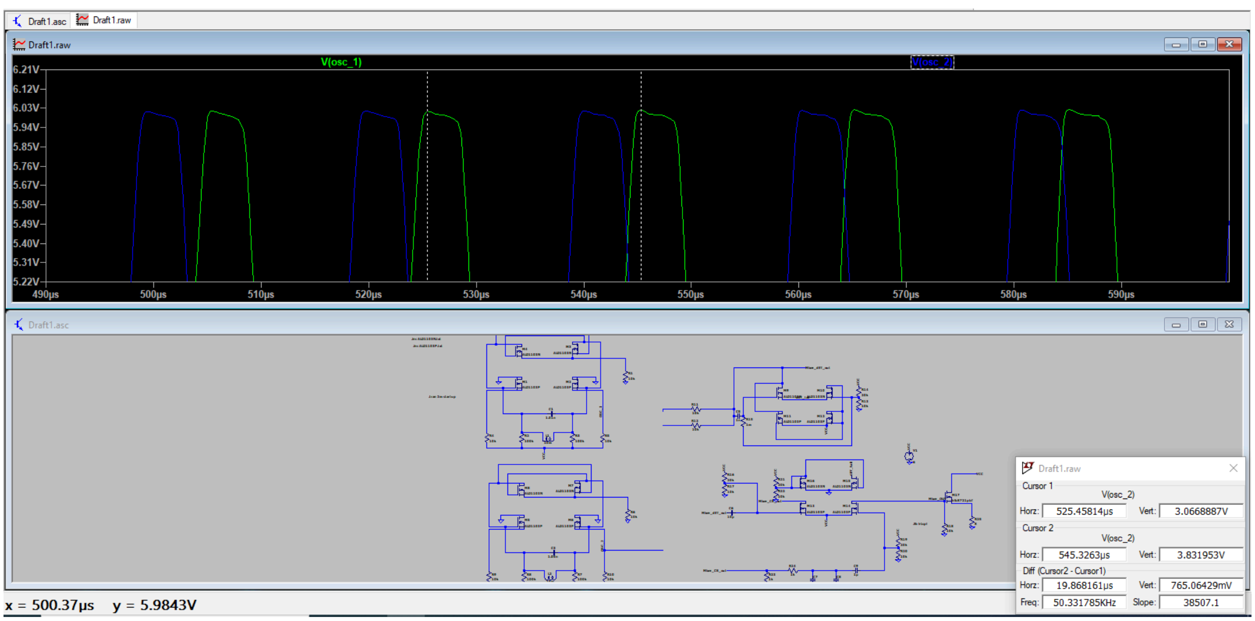

Figure 3: Oscillator A With 50kHz Frequency

Here, using a 1.01nF Capacitor with a 10mH frequency, Oscillator A shows a 50kHz frequency, which lines up with the equation discussed in the hand calculation section where frequency produced by an oscillator = $1/2\pi\sqrt{LC}$. Using this equation, 50.1 kHz is calculated.

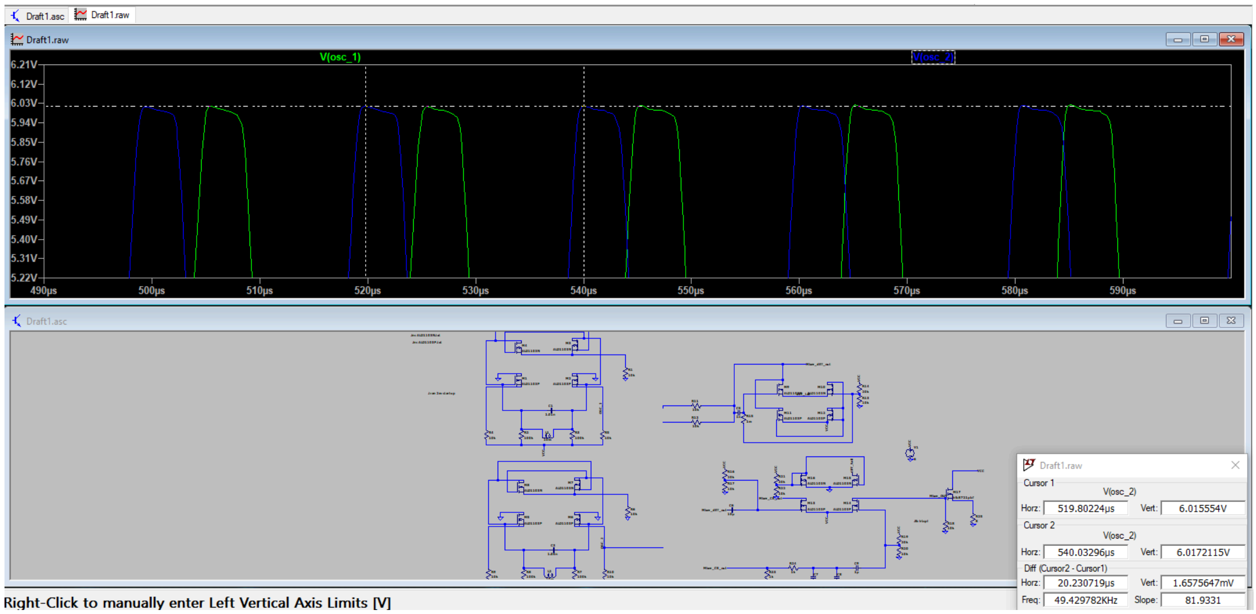

Figure 4: Oscillator 49kHz Frequency Verified

Here, using a 1.05nF Capacitor with a 10mH frequency, Oscillator A shows a 49kHz frequency, which lines up with the equation discussed in the hand calculation section where frequency produced by an oscillator = $1/2\pi\sqrt{LC}$. Using this equation, 49.1 kHz is calculated.

In the actual metal detector, the capacitor value was swapped here. For the sound to go from low to high, which is common in most metal detectors, the variable inductor oscillation frequency must start as higher than the non-variable frequency of oscillator A. Thus, to make a higher frequency than 50 kHz, a 680 pF + 220pF = 900 pF effective capacitor was used. This meant that the base variable frequency would be approximately 53.6 kHz (9.8 mH Inductor was winded as for the variable inductor), and then would get higher as metal came clos,e making a higher pitched noise.

Next, the inductance was changed to 10.5 mH on Oscillator B to emulate the Metal not being placed near the inductor. As expected, the frequency drops due to the inverse relationship.

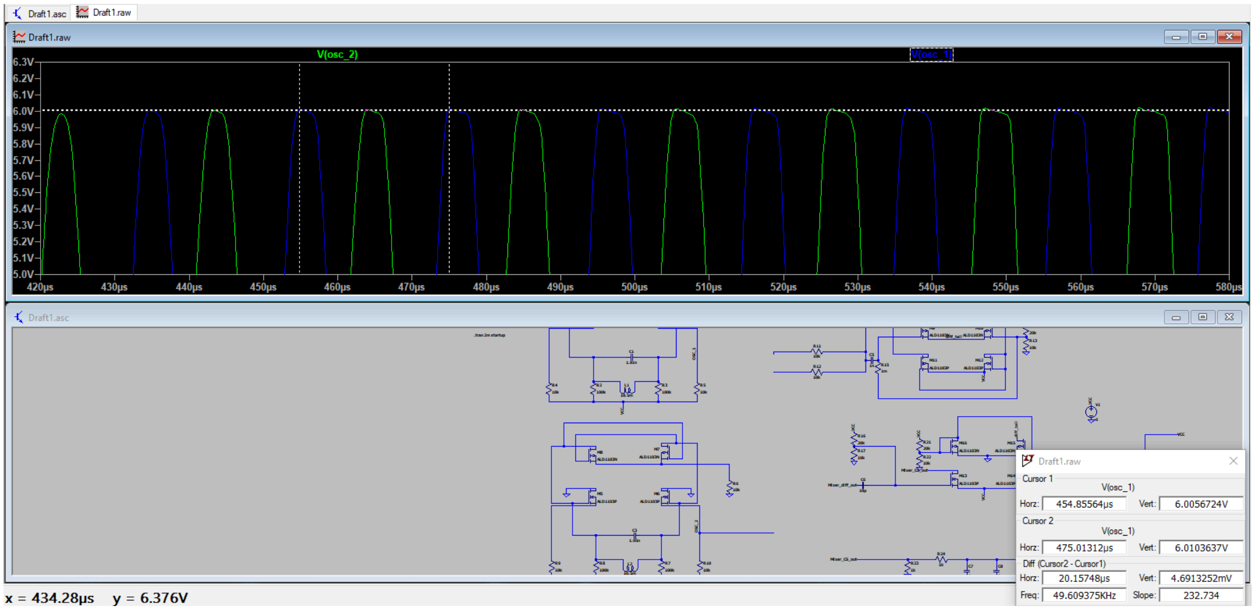

Figure 5: Oscillator B 5% Inductance Increase

The frequency is found to be 49.6 kHz, which lines up with C = 1.05nF and I = 10.5mH. Then, the output of the Mixer stage was measured similarly. First, without the inductance increase, and then with it.

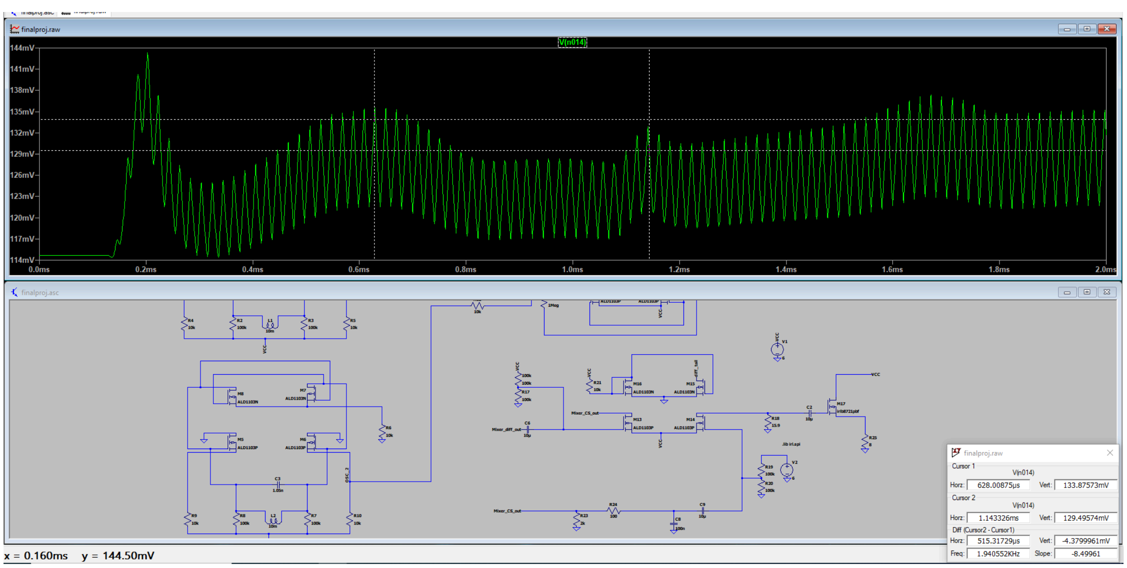

Figure 6: Mixer Output with 10mH inductance

Here, the measured "Frequency" or the gaps between the envelopes is 1.94 kHz (measured with cursors), which lines up nicely with what is expected. Here, the expected output is supposed to be equal to the difference between the two input oscillations.

In the actual metal detector, many changes were made. First, the bias points in the simulations were all biased to 3V. However, in the metal detector, different transistors were biased to certain values: Rv1 = 2.5V, Rv2 = 3.0V, Rv3 = 4.3V, Rv4 = 3.7V, Rv5 = 2.8V. Also, the low pass values were altered to be 100 Ohm and 50nF for a cutoff frequency of 31kHz using the equation used in the hand calculation section ($f_c = 1/2\pi RC$).

Here is the Mixer stage output with the impedance increase.

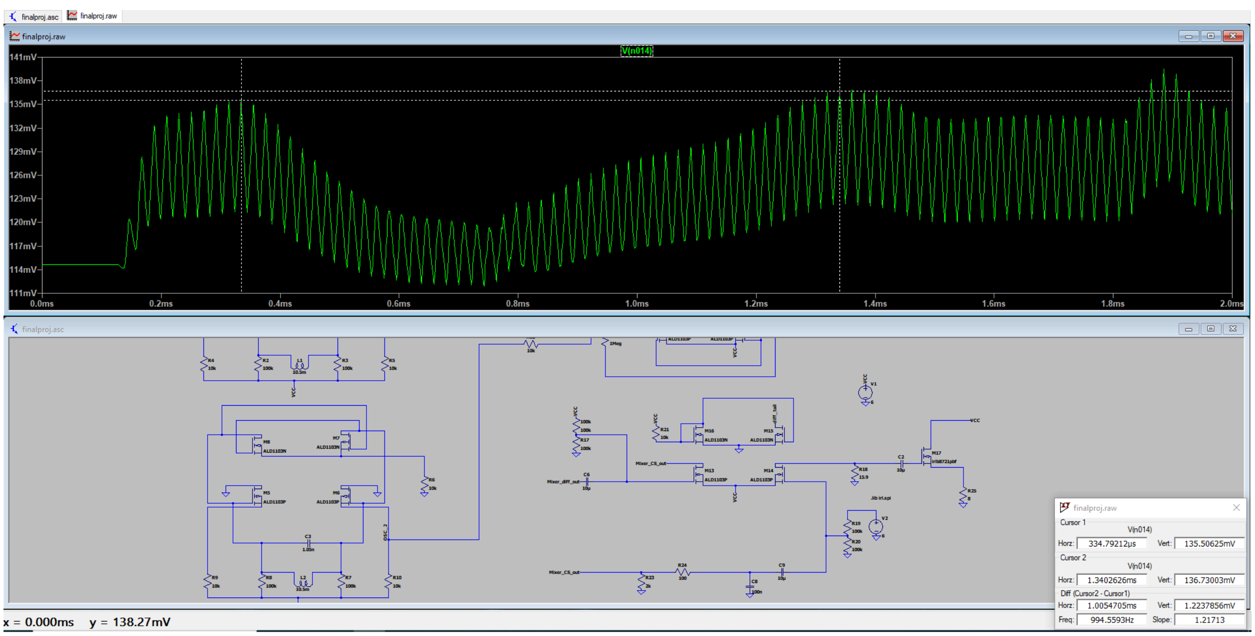

Figure 7: *Mixer Output with 10.5mH inductance*

Lastly, the output stage was also simulated with both impedances.

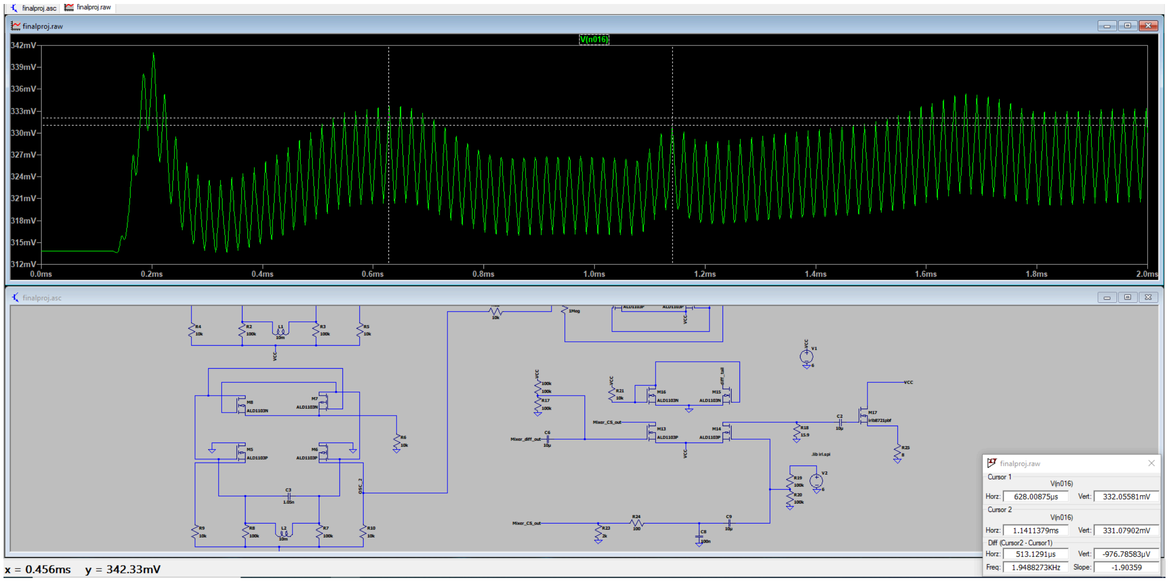

Figure 8: Final Output with 10mH inductance

Here, the envelope frequency is 1.94 kHz, measured with cursors.

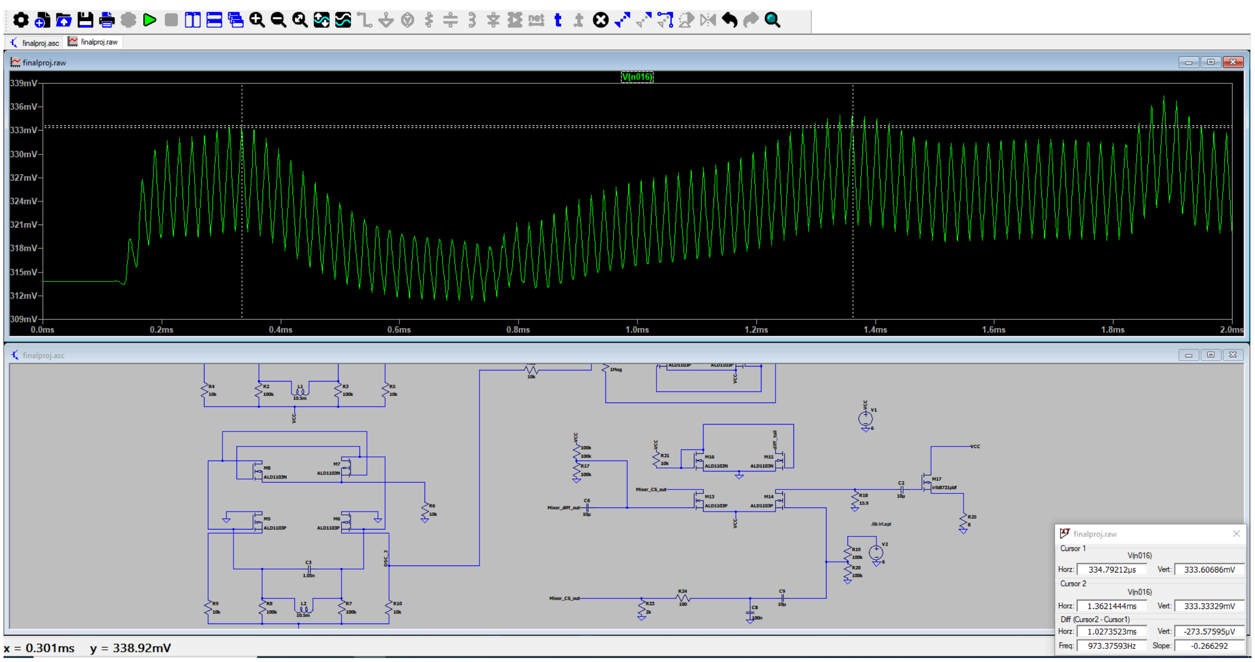

Figure 9: Final Output with 10.5mH inductance

Here, the envelope frequency is 973 Hz, measured with cursors. This drop makes sense as in the simulation, the variable frequency is lower initially. As the inductance increases (metal no longer near it), frequency gets higher, which would make the sound go from high to low.

PCB Layout

To build the metal detector, a custom PCB was designed and fabricated. This provided more reliable and stable connections compared to a breadboard. The organization below includes the main sections, including both Oscillators, the Mixer, the Differential Amplifier, and the Output. Input and Output ports will be designated below the image.

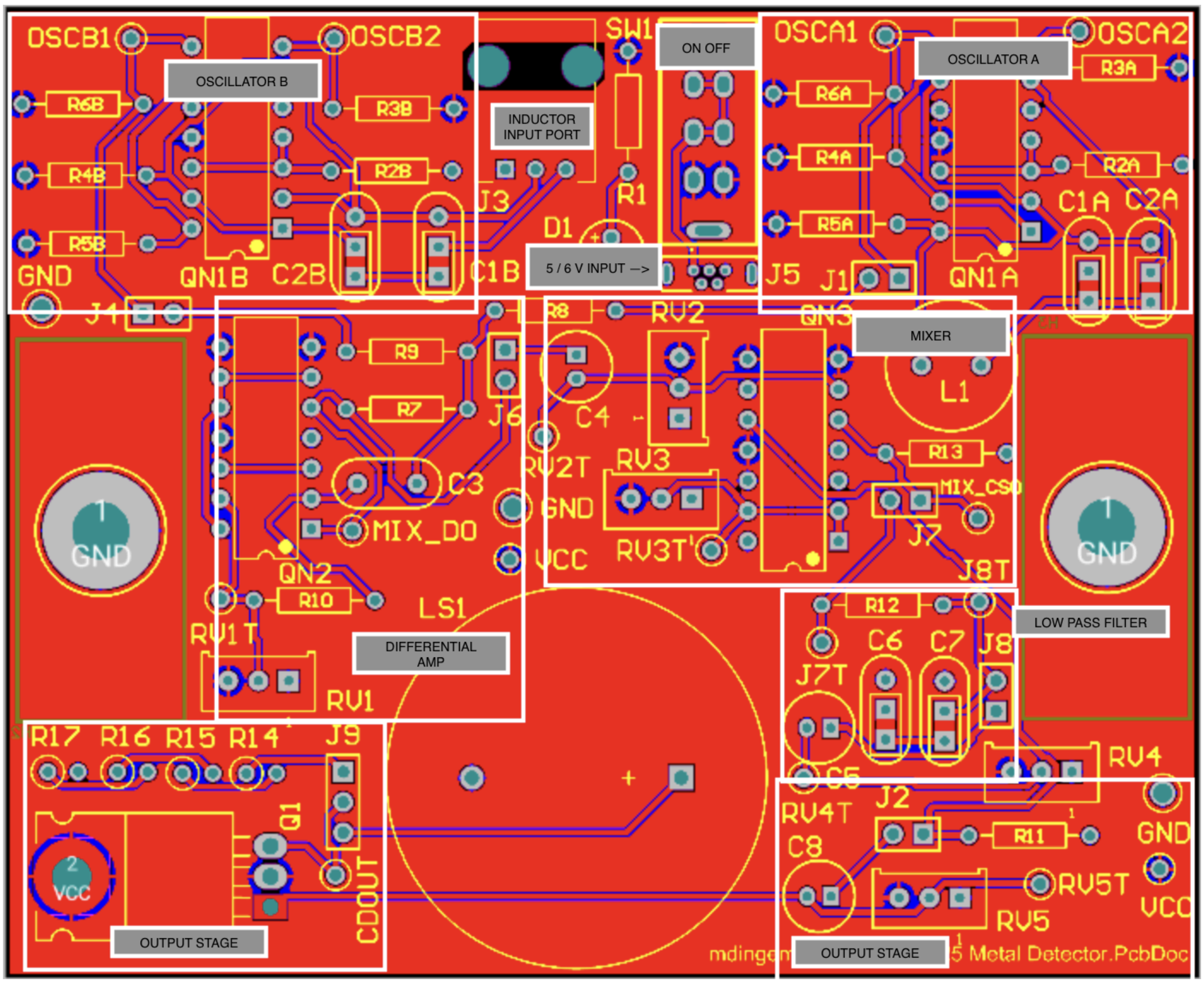

Figure 10: PCB Layout with Sections Labelled

Section	Input	Output (Test Point on PBC)
Oscillator A	VCC	OSCA1 and OSCA2
Oscillator B	VCC	OSCB1 and OSCB2
Differential Amp	J4/J1 and Oscillator Output	MIX_DO
Mixer CS Amp	J6	MIX_CSO
Low Pass	J7	RV4T
Mixer Out	J8	RV5T
CD Output (Final)	J2	CDOUT

Table 2: Input and Output Ports of PCB

These were the test points that were used to acquire the measurements in the following section: Measurement Results.

Measurement Results

In order to verify results, measurements were taken after every stage of the circuit. These stages included: both oscillators, the mixer's differential amplifier output, the mixer’s common source amplifier output, the mixer's common drain amplifier output, the RC low-pass output, and the final output. All measurements were taken with and without metal near the variable inductor to see how that affected the output.

First, the Oscillator stage was measured. Oscillator A is the nonvariable inductor, meaning it is not the one that is positioned at the end of the pole. As mentioned in the calculations section, the capacitor value used was 1nF, and the inductor was 10mH.

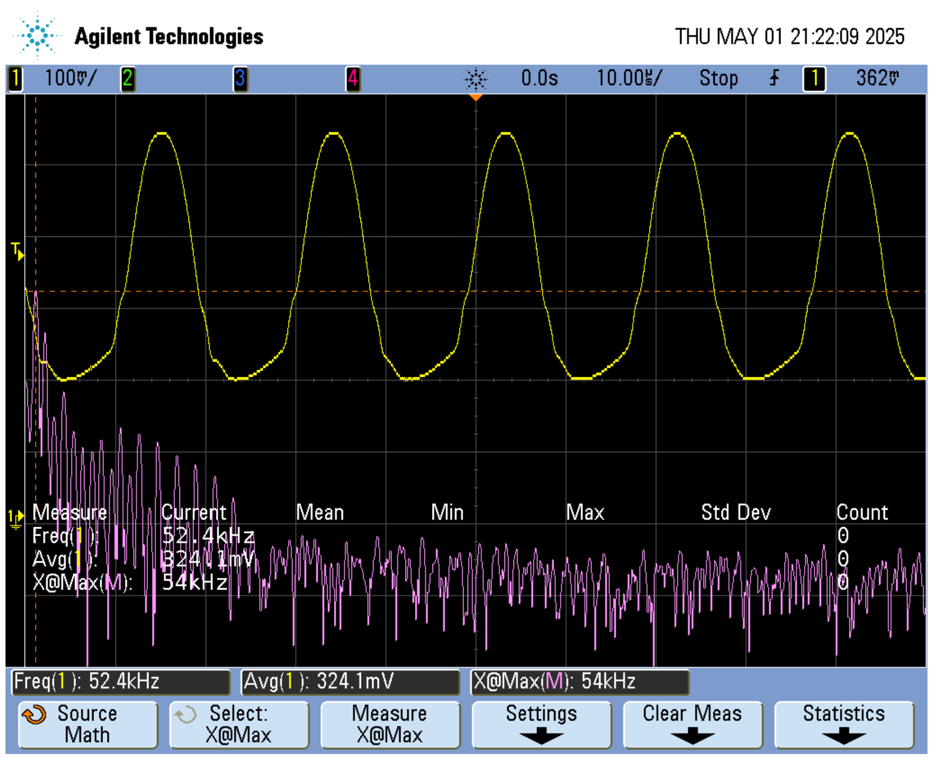

Figure 11: Oscillator A Output Without Metal

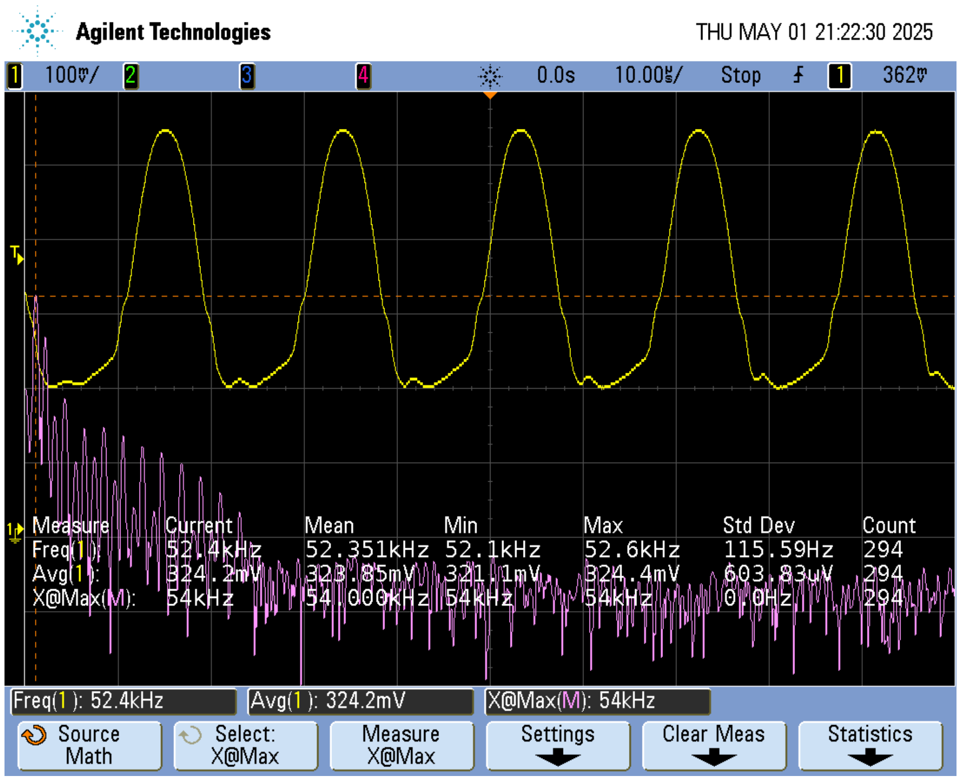

Figure 12: Oscillator A Output With Metal

As expected for the nonvariable inductor, the frequency with and without metal is the same: 52.4 kHz. Metal will not affect this frequency; only altering C1A and C2A will. The measured frequency aligned nicely with the expected value from the calculation $1/2\pi\sqrt{LC}$, which results in 50.3 kHz. This difference can be accounted for by capacitor and inductor tolerances.

Then, Oscillator B was measured with and without metal. This is the variable oscillator, which means that the metal will affect it. The capacitor values chosen here were 680pF + 220pF = 900pF. This capacitance value was chosen because it'll make the base frequency without metal higher than Oscillator A's frequency. Thus, when the metal is brought near, Eddy currents are induced in the metal which oppose the magnetic field and reduce the effective inductance, making the output frequency *higher*, making the output sound higher pitched than the base sound. This is true because of the inverse relationship in the frequency equation. (Inductance in denominator).

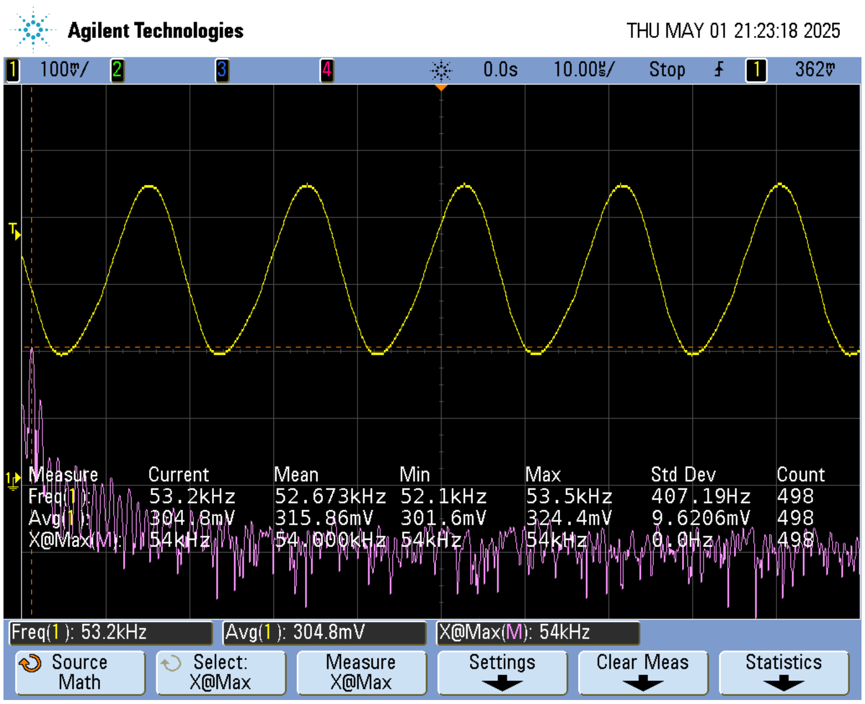

Figure 13: Oscillator B Output Without Metal

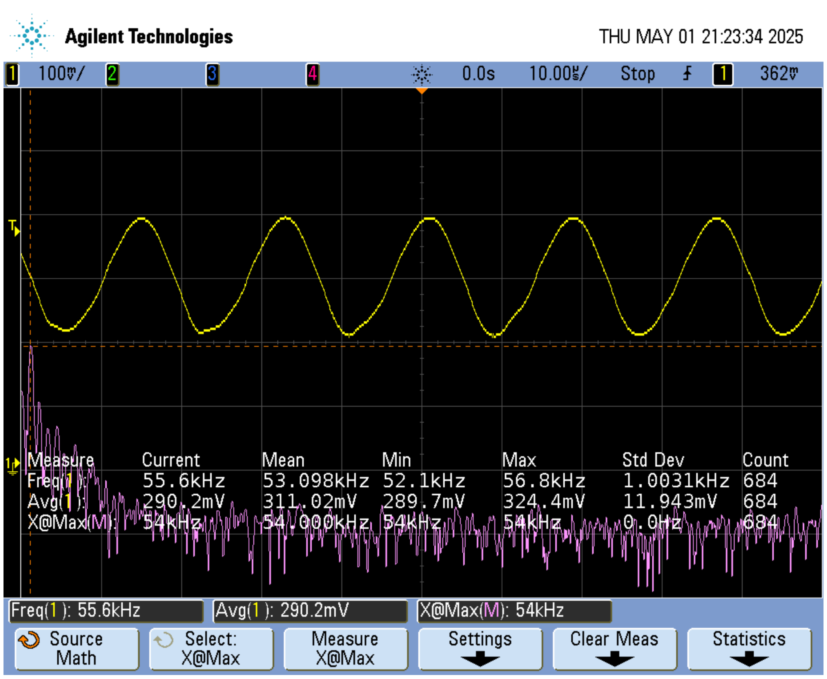

Figure 14: Oscillator B Output With Metal

Without metal, the measured oscillation frequency was 53.2kHz, which lines up nicely with a C = 900pF and L = 9.8mH. The calculation gives 53.6kHz using $1/2\pi\sqrt{LC}$, which is very close to the measured. Then, when metal is applied, the frequency jumps to 55.6kHz, which as discussed, makes sense as the inductance lowers, and thus frequency rises.

Thus, at base, the difference will be 0.8kHz, and when metal is applied, the difference jumps up to around 3.2kHz, making that change in audible pitch, indicating metal is near.

Next, the Mixer Differential Output was measured. Rv1 was tuned to 2.5V and Rv3 was tuned to 4.3V. These control the bias voltages of the differential pair amplifier.

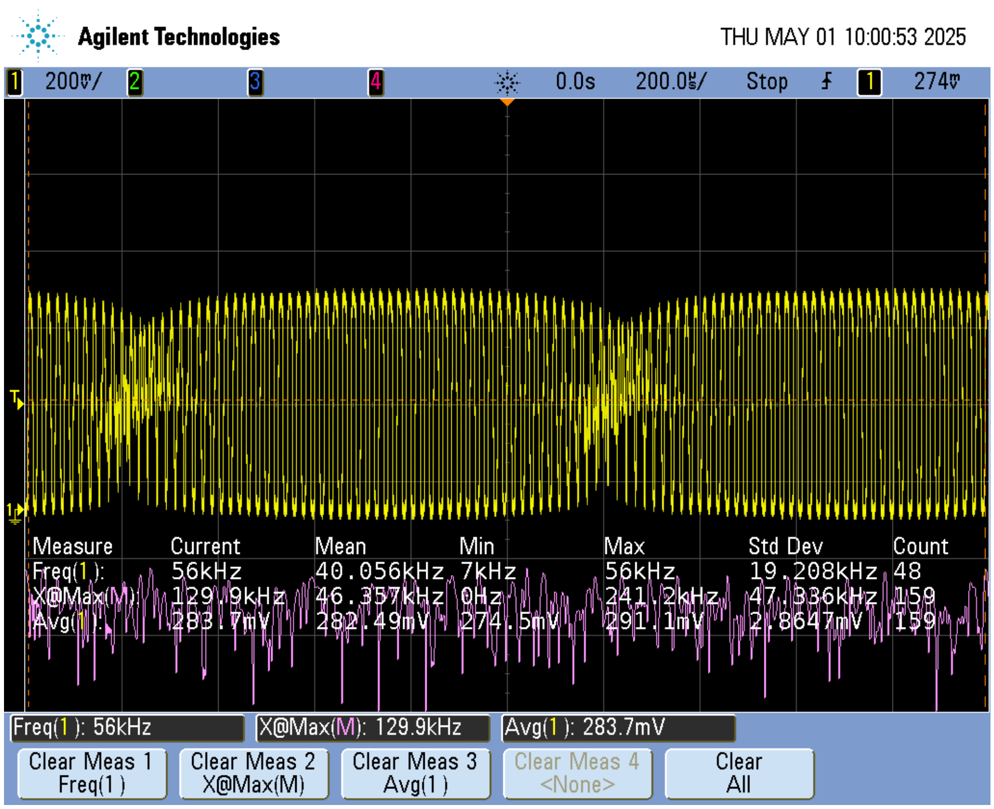

Figure 15: Mixer Differential Output Without Metal

Here, an enveloping effect can be seen. Once the metal is placed on the variable inductor, the envelopes get smaller, which makes sense as the frequencies get bigger

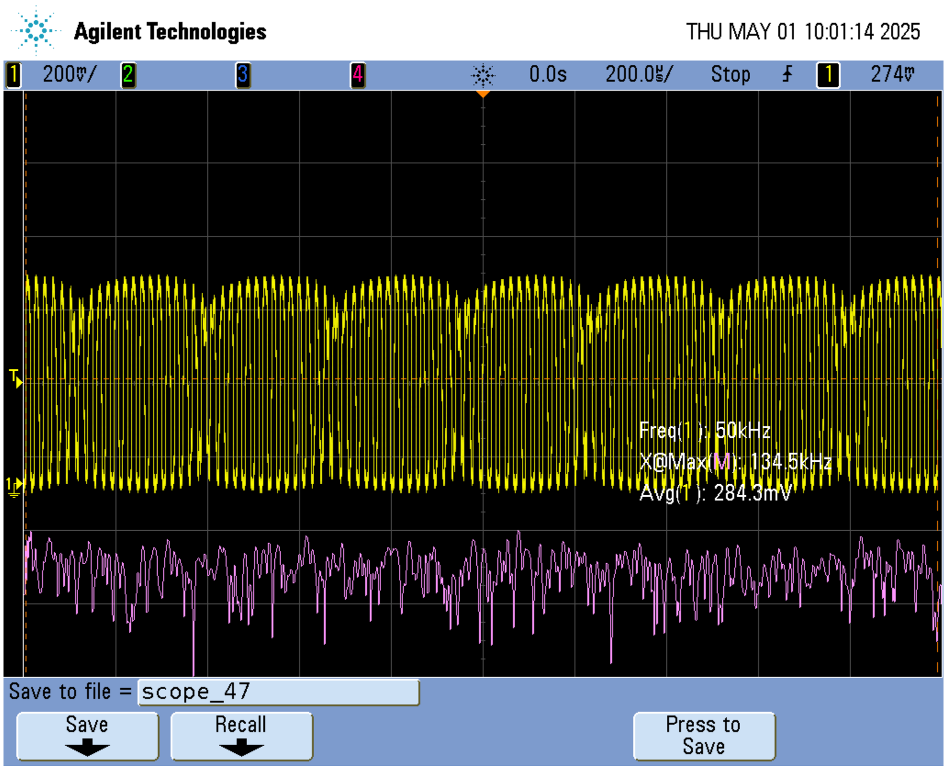

Figure 16: Mixer Differential Output With Metal

This output is expected. There are around 1-2kHz envelopes that represent the difference between the fed signals, where the presence of metal raises the frequencies.

Next, the Mixer Common Source Amplifier is used to boost the difference signal. Rv2, which tunes the CS Amp, was biased to 3.0V, similar to the prelab.

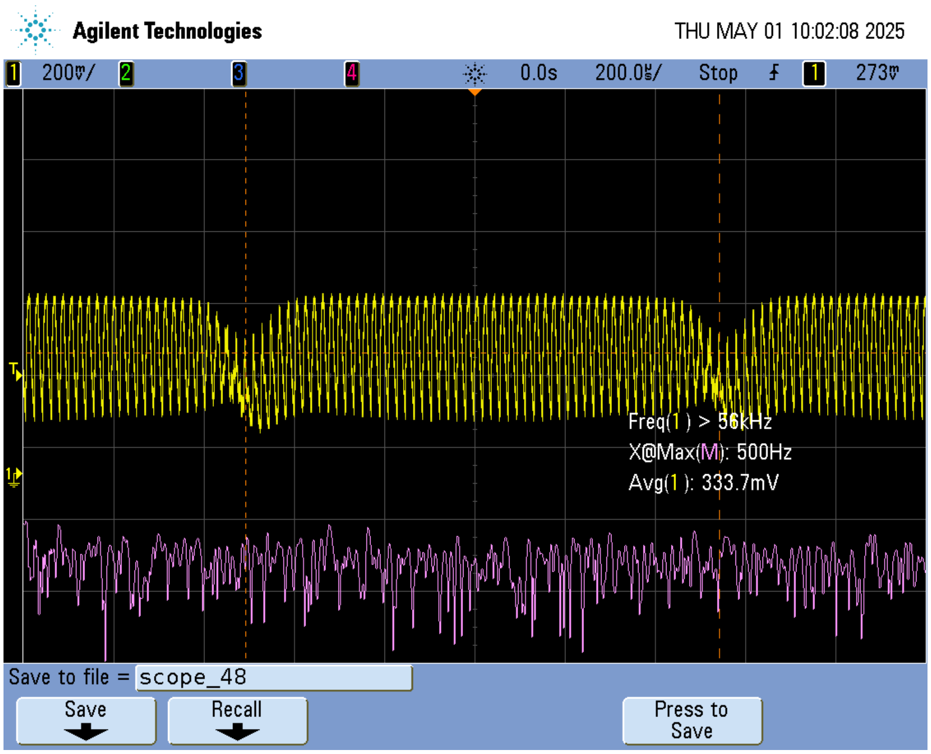

Figure 17: Mixer CS Output Without Metal

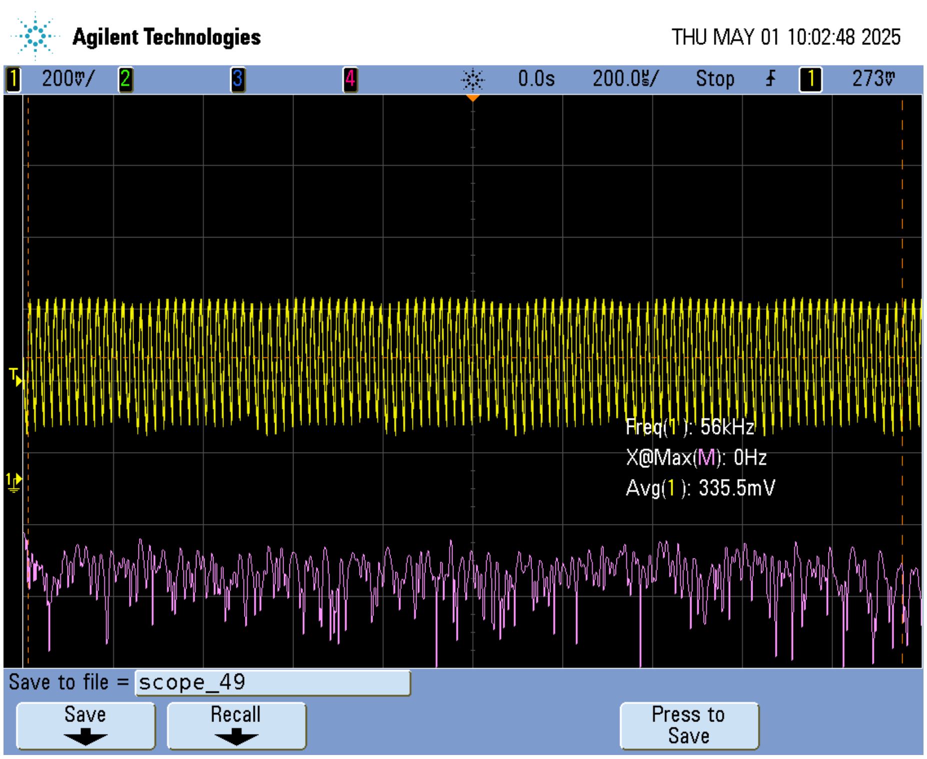

Figure 18: Mixer CS Output With Metal

Here, similarly to the differential output stage, there is a higher frequency when the metal is placed near. The envelopes are still visible, but as expected, the common source amplifier stage has amplified our signal slightly.

Next is the low-pass filter. The values for the low-pass filter were 100 Ohm for the resistor (R12 in the schematic) and 50nF for the capacitor (C6 in the schematic). These values varied from the prelab quite significantly, and together, using the cutoff frequency equation, $f_c = 1/2\pi RC = 31.8kHz$ which is a good value as it is above the expected difference but below 50kHz. Rv4, which tunes the mixer output gate, was tuned to be 3.7V.

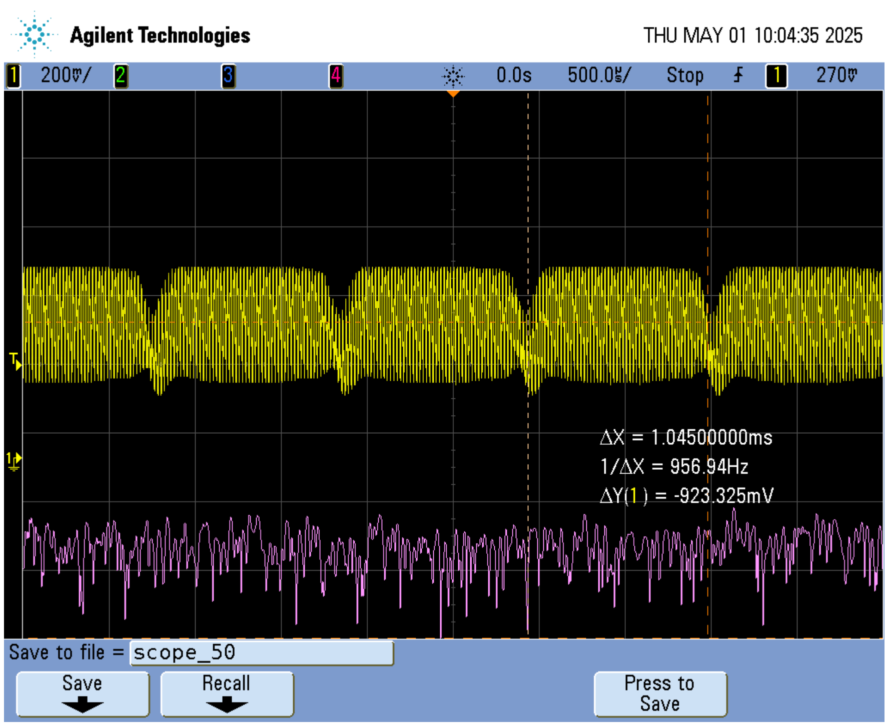

Figure 19: Low Pass Output Without Metal

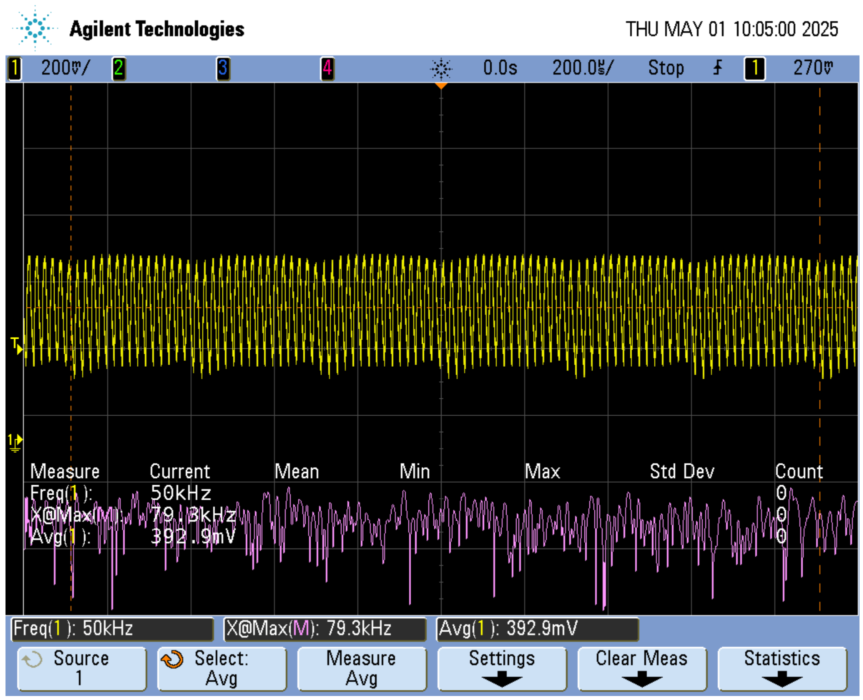

Figure 20: Low Pass Output With Metal

This matches what is expected. Metal makes the frequencies higher as the variable inductor gets higher, and the mixer gives the difference.

Next is the Mixer Output. This is the stage before the IRLB8721PBF FET transistor. Rv5 was tuned to 2.8V, which is the gate of the FET.

Figure 21: Mixer Output Without Metal

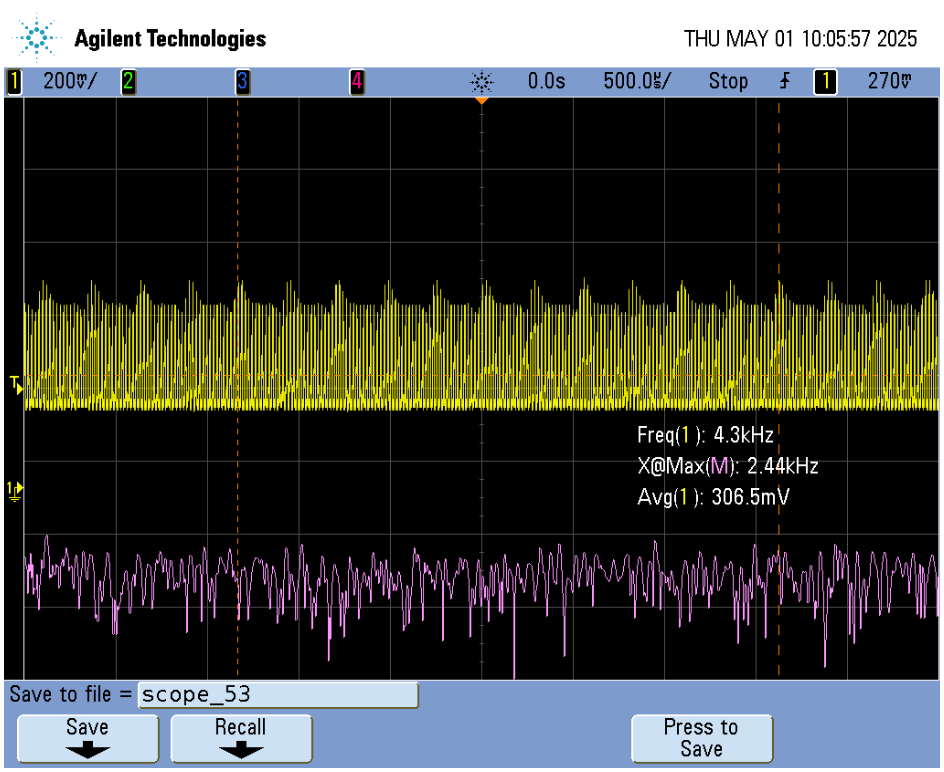

Figure 22: Mixer Output With Metal

Lastly, the output of the final stage is shown below.

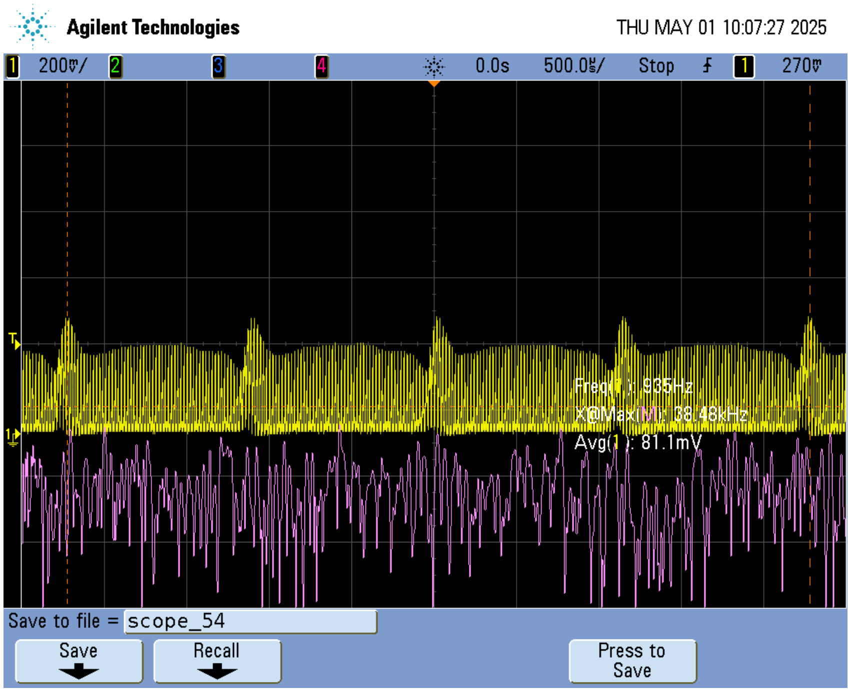

Figure 23: Final Output (CD_OUT) Without Metal

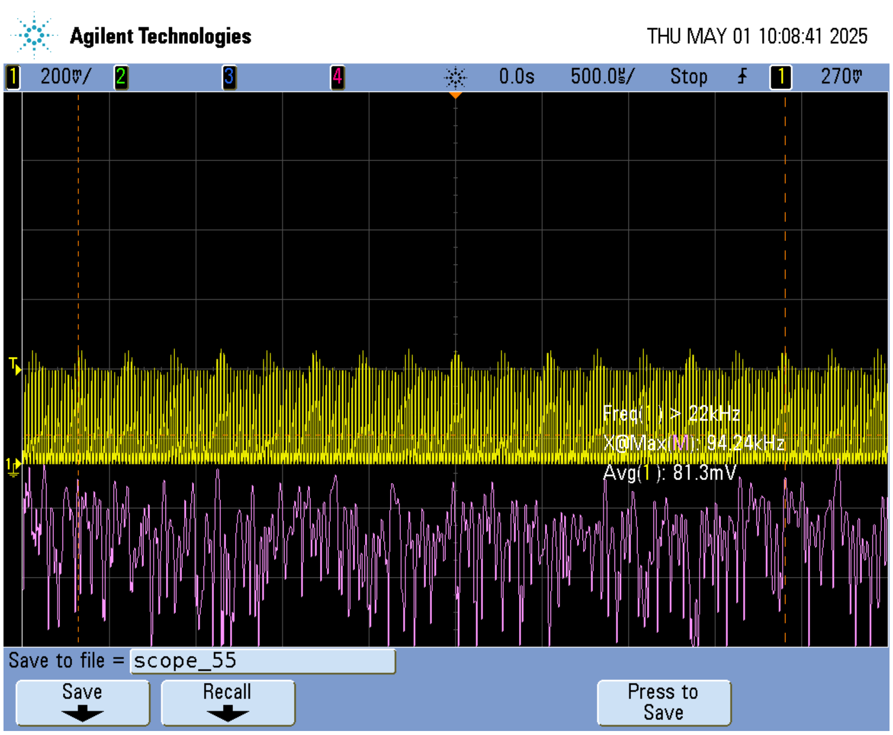

Figure 24: Final Output (CD_OUT) With Metal

The output is what is expected. The Common drain amplifier outputs a low impedance output to the speaker, which then plays the inputted mixed frequency, which is the difference between the two oscillations, which change as metal goes near. The difference gets bigger when metal is near, allowing the speaker to play a higher-pitched noise.

Discussion

The measurements, hand calculations, and simulation results were all promising. The simulation values for some of the later stages were changed in the actual construction of the metal detector, so the outputs do not match as nicely.

For the oscillator stages, the hand calculation, simulation, and measurements lined up well. For Oscillator A, a calculated value of 50.3 kHz lined up well with a simulation value of 50.3 kHz and a measurement value of 52.4 kHz. This output measurement is slightly higher, likely due to tolerances in the components. Oscillator B similarly had very close values, with 53.6 kHz for hand calculation, 53.2 kHz for the simulation, and 53.2 kHz for the measurement.

The mixer stage had a 1.94 kHz simulation enveloped frequency without metal, and then a 973 Hz envelope frequency with metal. This lined up nicely with the oscilloscope outputs, which changed from around 900 Hz to probably around 2 kHz with metal. This flip effect is because in the simulation, the base variable oscillation value was lower and would get higher, meaning the difference would shrink, but in the actual metal detector, the original variable oscillator frequency is higher, so the difference goes up when metal is near.

The simulation low-pass filter used a 100 nF capacitor and a 100 ohm resistor, which resulted in a low-pass filter of 15 kHz, but in the actual metal detector, the capacitor value was changed to 50 nF, doubling the cutoff to around 30 kHz after experimenting in person.

Lastly, the CS amplifier gain was hand calculated to be 46. The actual gain seems to be lower, as the amplitudes do not seem to grow as much after the CS amplifier stage. This is likely due to the transistor being more along the edge of saturation and triode, whereas the calculation assumes perfect biasing.

Conclusion

This final project was a good culmination of many of the prior labs, such as the mixer lab, oscillator lab, and all the amplifier labs. It was helpful to see all of the parts used together to see all of their different uses in context.

The most difficult part of this project was simulating the results of each stage in order to get the desired outputs. Building the circuit in LTSpice and then calculating certain parameters that were not given was tricky, but doing so ensured that each stage was understood individually and its role in the overall product.

By constructing a metal detector, a deeper understanding of how oscillators, mixers, amplifiers, filters, and output drivers interact in a complex circuit was gained. It was especially helpful to see how each block contributes to a complex and purposeful tool when combined. This gave a much stronger intuition for how signal processing chains are designed, even if it is shorter.

In order to make the design better, more amplifiers could have been used to increase sensitivity. During the demo, some of the squares that contained metal were not detected because the audio did not switch from a low pitch to a high pitch at an audible enough change. The signal generated by the oscillator-mixer path was likely too weak to produce a discernible audio difference when interacting with small or low-conductivity objects. Increasing the gain in the differential amplifier could ensure that small frequency changes result in audible feedback.

Overall, this lab provided a great opportunity to integrate many of the concepts learned throughout the semester. It was valuable to see the versatility of all the tools and techniques that have been studied this year in practice.

Acknowledgements

Thank you to Professor Farmer for this course. It has been a lot of work, but definitely a good experience, and I have learned a lot!

It has also been a pleasure taking this course with such amazing teaching assistants. If I were ever struggling in this course, I knew I would be able to figure it out with all your help, no matter what it was. I hope you all have wonderful summers!

References

All Lab Documents and Schematics given