ESE 319

FINAL PROJECT: METAL DETECTOR

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Introduction

The purpose of this project is to design and construct a metal detector. Leading up to this project, we had a couple labs to obtain knowledge on the separate components: oscillator, mixer, and output stage. The idea behind the design is to have a large custom-coil inductor that changes inductance based on proximity of a metal object, and this changed inductance will produce a different-frequency output from its partner oscillator, the difference of which will be revealed by the mixer, and finalized by the output stage to be played by the speaker. The application of this project is to use it as a metal detector: when the coil is brought near and facing a metal object, the speaker will play a frequency, higher as the coil comes closer and closer to the metal object. In a perfect metal detector, the speaker should play no noise when no metal is nearby.

Design Strategy

The system architecture of the metal detector is comprised of two oscillators, one with a custom inductor, the outputs of which are fed into a mixer, the output of which is then fed into an output stage which passes it along to the final speaker. The oscillators produce sinusoidal waves from DC signal. The custom coil for oscillator 1 is set at the base of the metal detector so that its inductance will change, based on proximity of metal. The mixer takes in the production of the two oscillators, and outputs the difference between the two frequencies. The output stage prepares the difference signal to be played by the small-load final speaker. See Fig. 1 for a block diagram of the electronics.

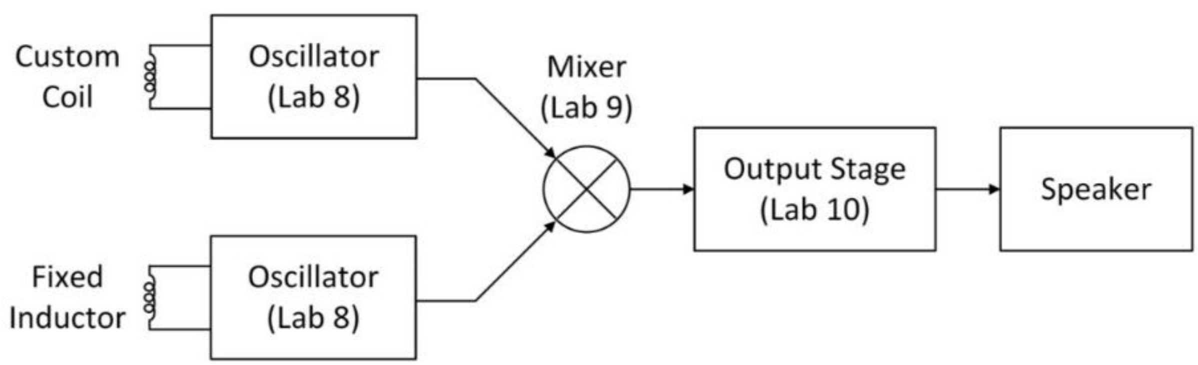


Figure 1: (Taken from Lab_S18_Final Project Part I.pdf) Block diagram of the electronics component of final project.

The electronics are put on a long PVC pipe, and powered by a DC battery, to create the final product.

Hand Calculation

Stage 1: LC Oscillator

Calculation of L and C:

We want to construct the LC Oscillator to have a 100kHz output. We chose 100kHz because this is a sufficiently high frequency to notice a difference, and yields capacitor and inductor values readily available in Detkin laboratory.

Goal frequency: 100kHz

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

$$100kHz = \frac{1}{2\pi\sqrt{2*10^{-3}*1.3*10^{-9}}}$$

L = 2mH ; C = 1.3nF

Calculation of N:

In order to make the custom coil, we want to make it as close to 2mH as possible, in order to match the inductor on the other oscillator.

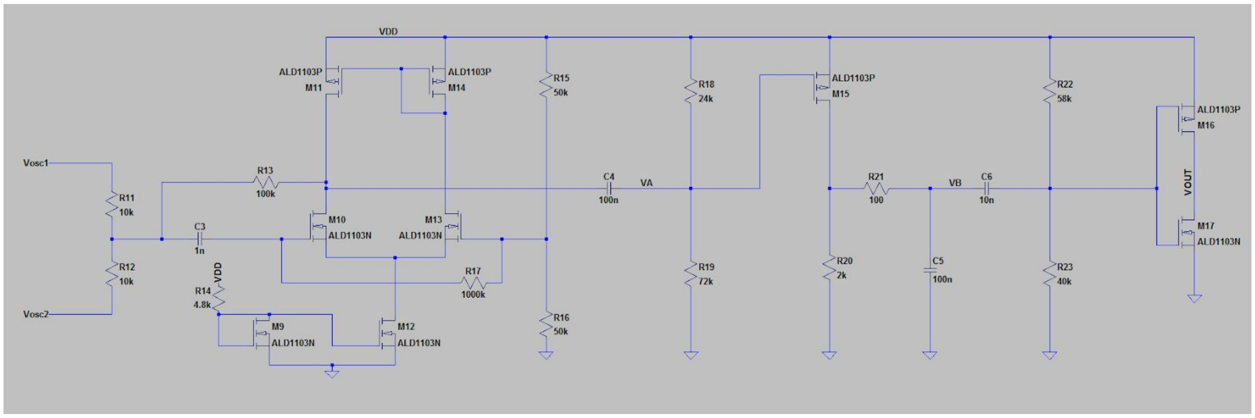
Goal inductance: 2mH
D = 4in; H = 0.25in

$$L = \frac{D^2*N^2}{18D + 40H}$$

$$2000uH = \frac{4^2*N^2}{18*4 + 40*0.25}$$

N = 101 turns.

Stage 2: Mixer



For reference, the schematic with labelled transistors is above.

We want all amplifiers in the differential amplifier to be in saturation. Calculate biasing points:

$$|V_{DS}| \geq |V_{GS}| - |V_{TH}|$$

M10:

$V_{D10} \geq V_{G10} - 0.7$

$V_{D10} = \frac{72}{72+24} * 6 = 4.5V$ by voltage divider

$4.5 \geq V_{G10} - 0.7$

$V_{G10} \leq 5.2$

M11:

$6 - V_{D11} \geq 6 - V_{G11} - 0.8$

$V_{D11} = V_{D10} = 4.5$

$1.5 \geq 6 - V_{G11} - 0.8$

$V_{G11} \geq 3.7$

M9:

$V_{D9} \geq V_{G9} - 0.7$

$V_{D9} = V_{G9}$

$V_{D9} \geq V_{D9} - 0.7$ always

M12:

$V_{D12} \geq V_{G12} - 0.7$

M13:

$V_{D13} \geq V_{G13} - 0.7$

$V_{D13} \geq 3 - 0.7$

$V_{D13} \geq 2.3$

M14:

$6 - V_{D14} \geq 6 - V_{G14} - 0.8$

$V_{D14} = V_{G14}$

$V_{D14} \geq V_{D14} - 0.8$ always

Stage 3: Output stage

Gain:

The voltage gain of a push-pull amplifier is unity, as it is a common source-follower. The purpose of the output stage is to provide a current gain, and the more stages are added, the larger that current gain, as each added amplifier produces more current for the final V_{OUT}. For class B "push-pull" amplifiers, $V_{OUT} = V_{IN} - V_{GS.}$

We can see the output stage as a series of common-drain source followers. The gain of a source follower amp is:

$$A_V = \frac{g_m R_S \| r_o}{1+(g_m+g_{mb})R_S \| r_o}$$
$$= \frac{g_m R_S r_o}{R_S + r_o + (g_m+g_{mb})R_S r_o}$$
$$\approx \frac{g_m}{g_m+g_{mb}} \approx 1$$

And thus, the gain of the output stage should be ~<1.

Simulation Results

Stage 1: Oscillator:

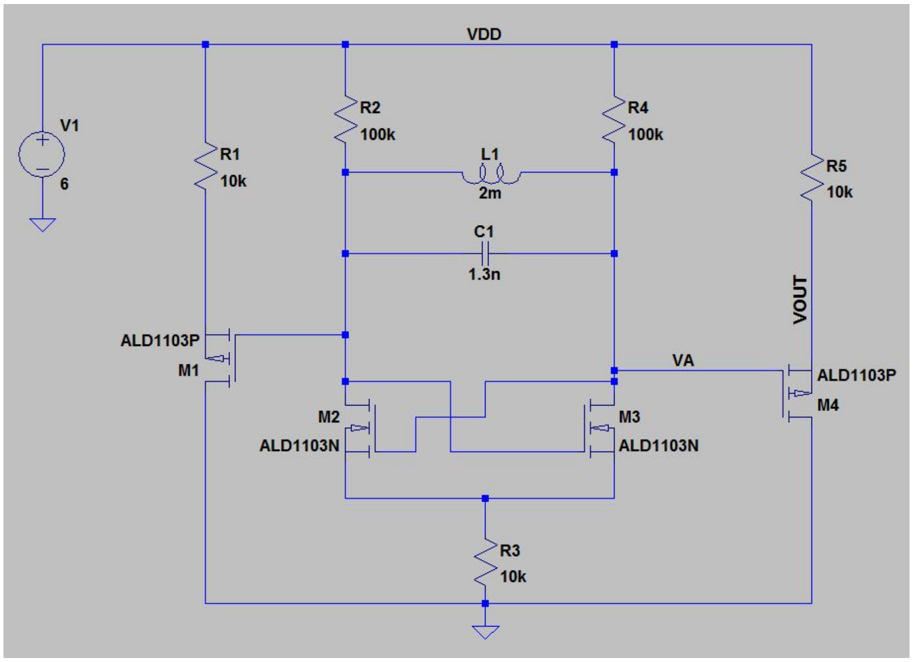


Figure 2: LTSpice schematic for oscillator.

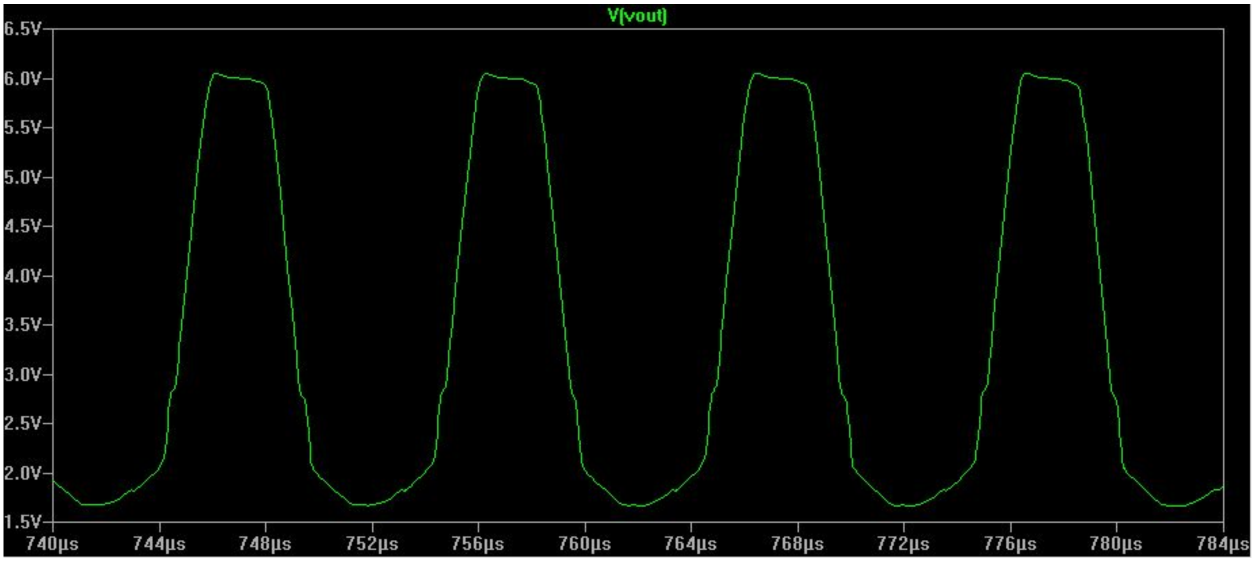


Figure 3: LTSpice simulation for oscillator. Produced frequency: 98.7kHz

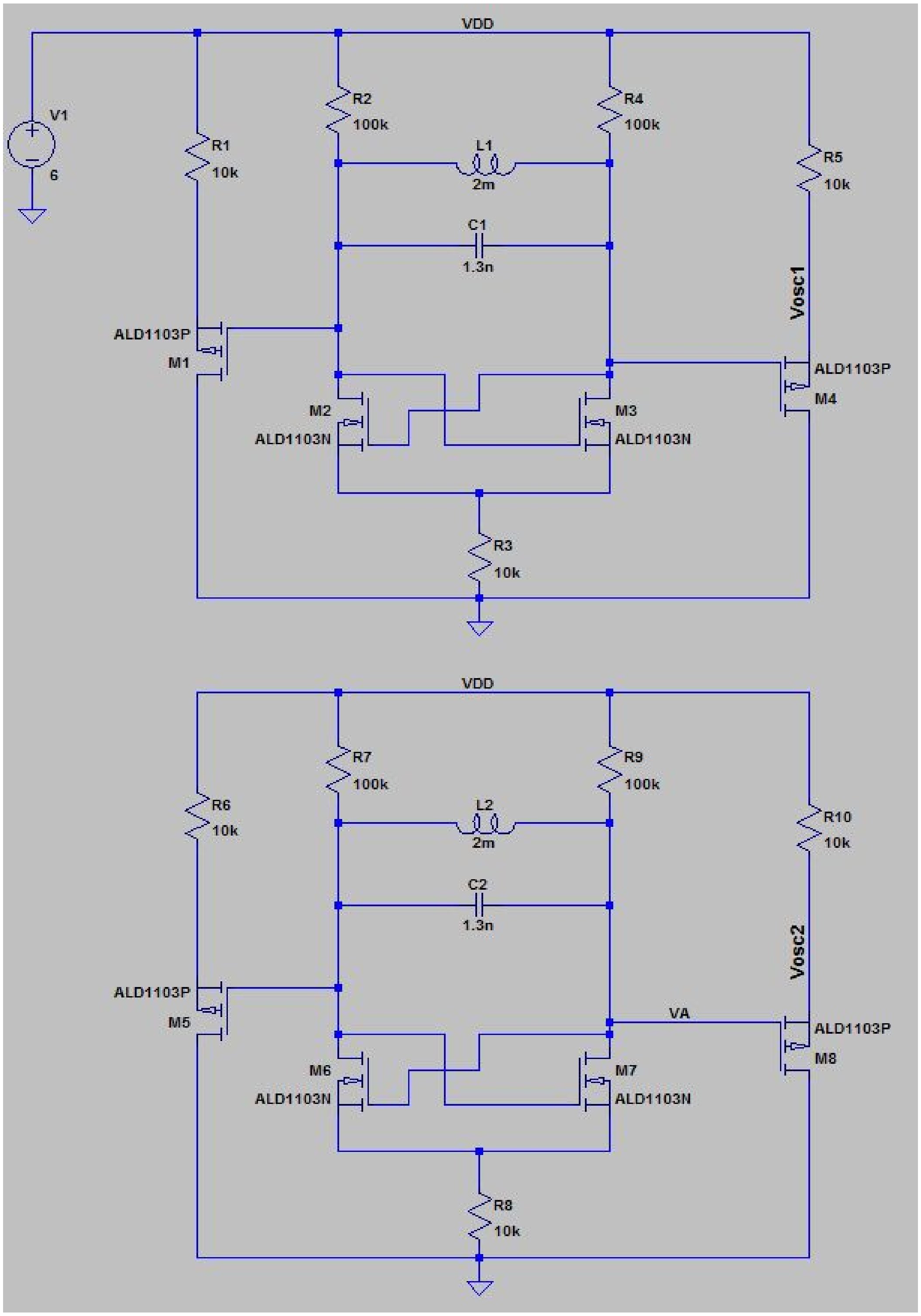


Figure 4: LTSpice schematic for both oscillators. L1 is the variable inductor.

Now, changing the value of L1 in order to see the effect on output signal:

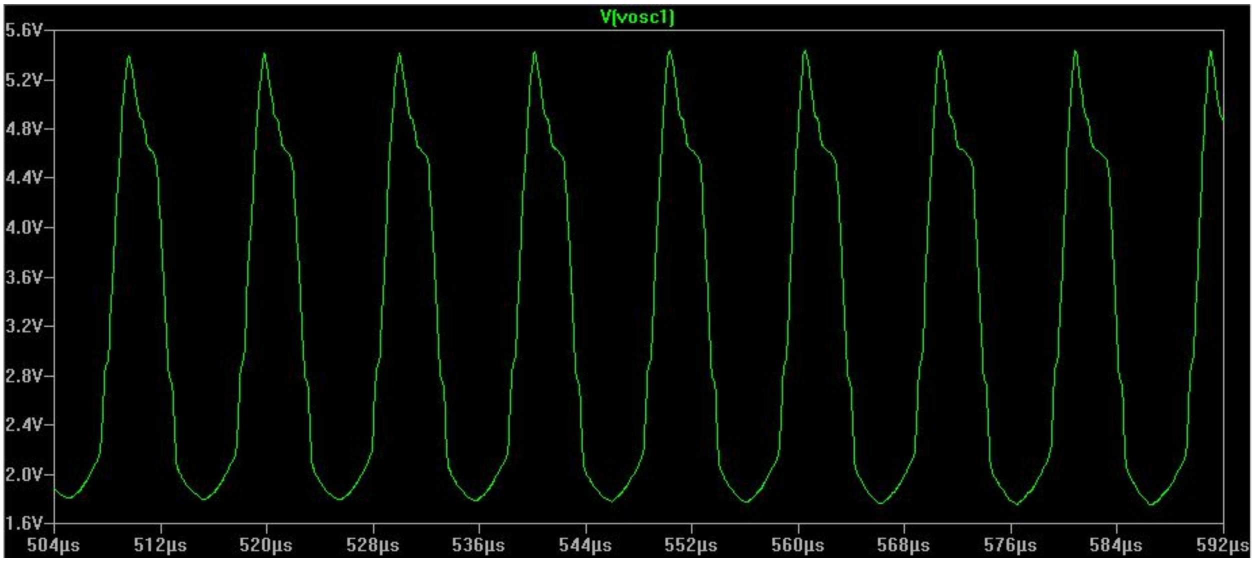


Figure 5: LTSpice simulation with L1 at 1% inductance difference: L = 2.02mH. Produced frequency: 98.2kHz

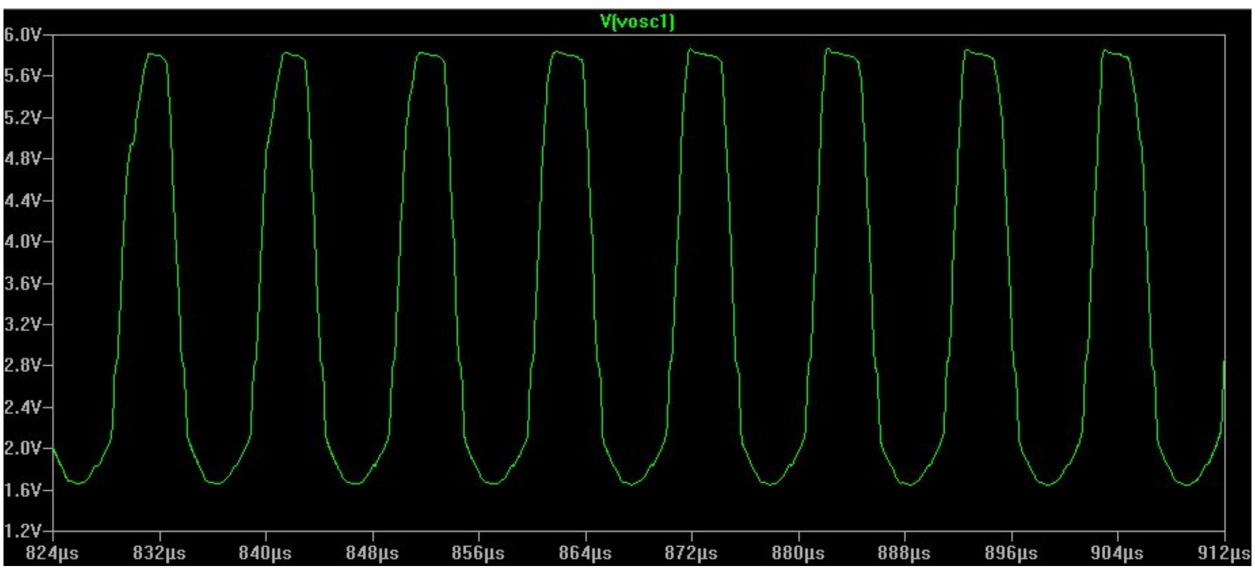


Figure 6: LTSpice simulation with L1 at 5% inductance difference: L = 2.1mH. Produced frequency: 96.3kHz

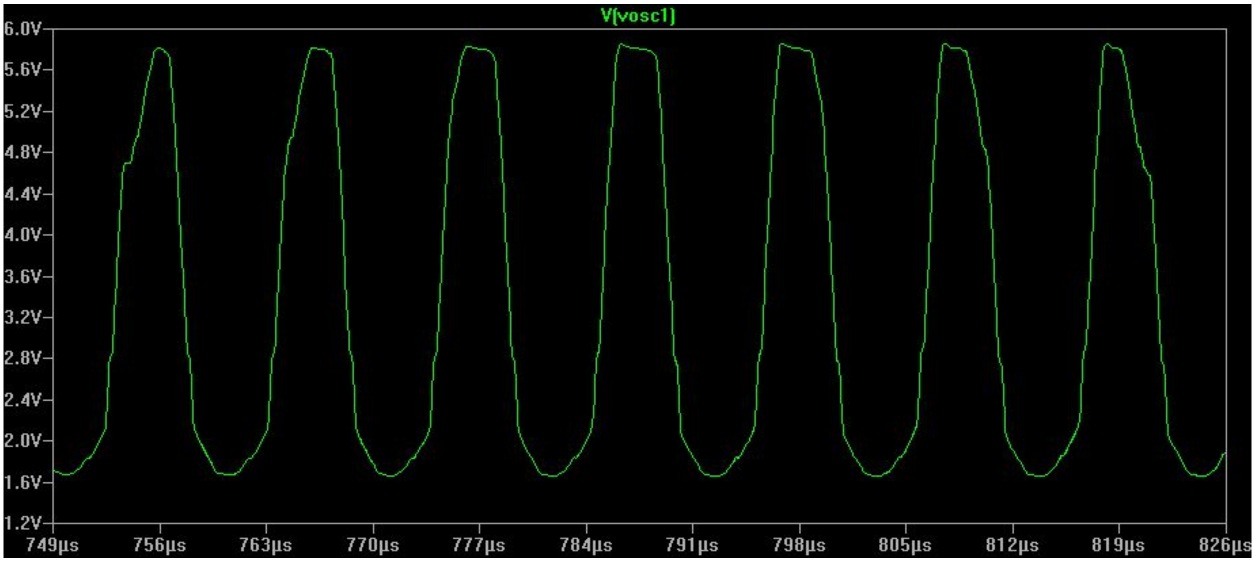


Figure 7: LTSpice simulation with L1 at 10% inductance difference: L = 2.2mH. Produced frequency: 94.1kHz

We observe that as inductance of L1 increases, produced frequency decreases.

<u>Stage 2: Mixer:</u>

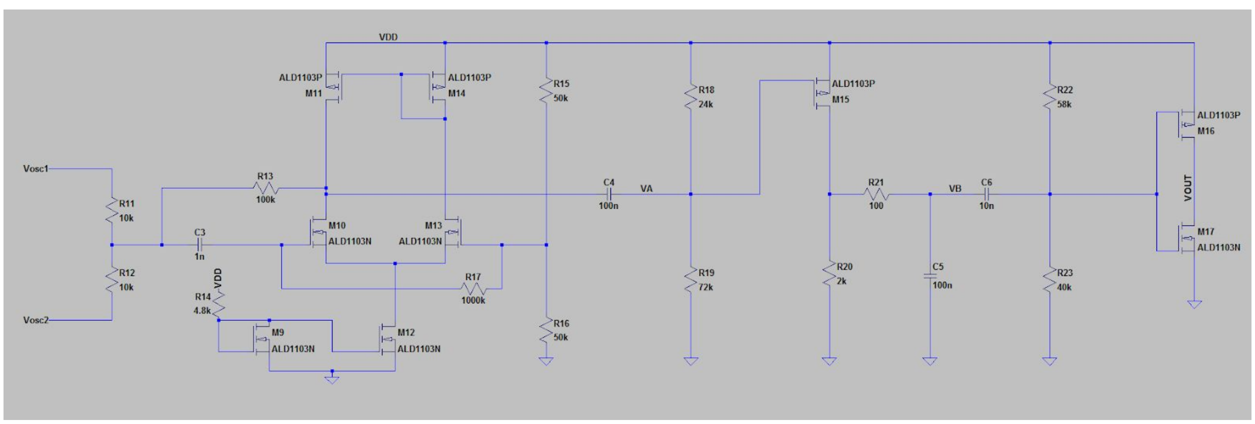


Figure 8: LTSpice schematic for mixer.

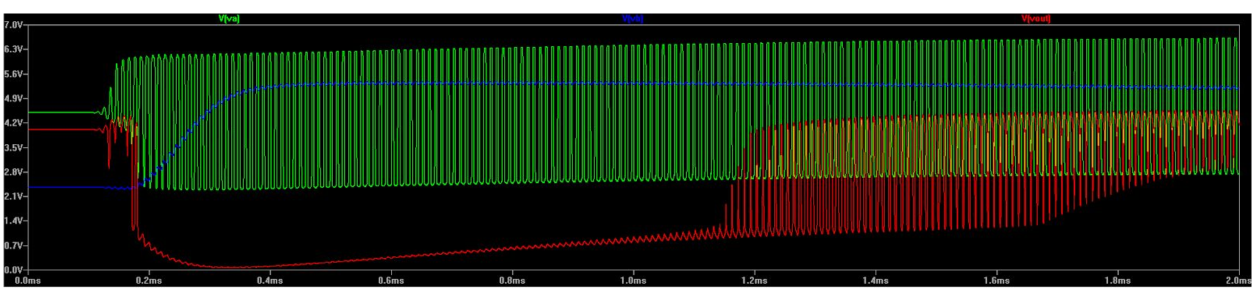


Figure 9: LTSpice simulation output with both inductors at 2mH: no frequency in output.

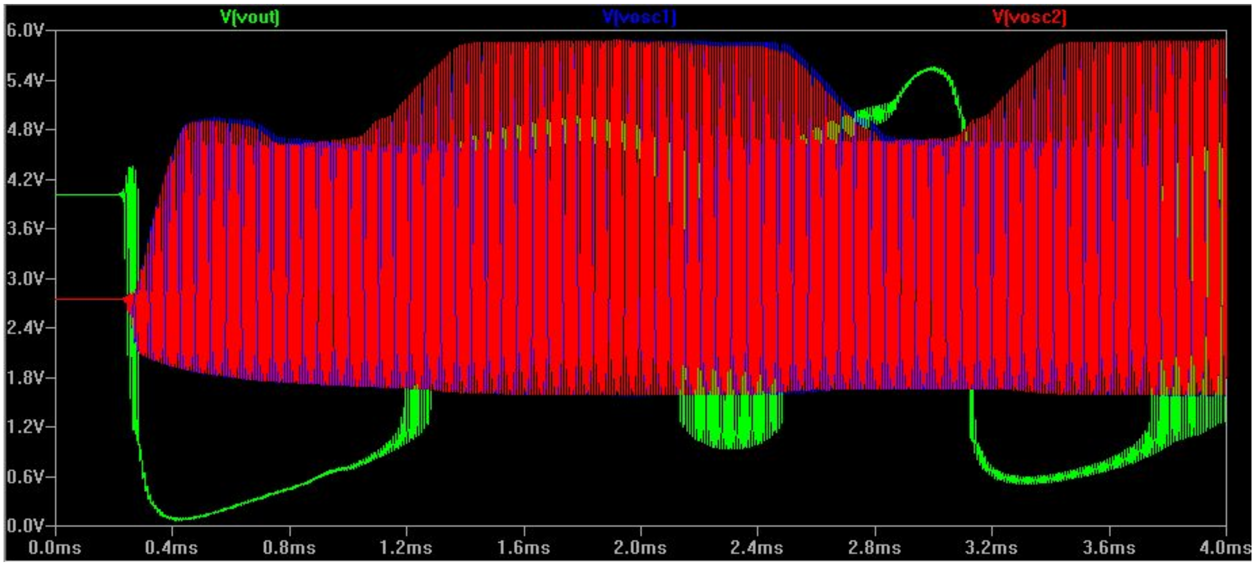


Figure 10: LTSpice simulation output with variable inductor at 2.02mH: frequency in output.

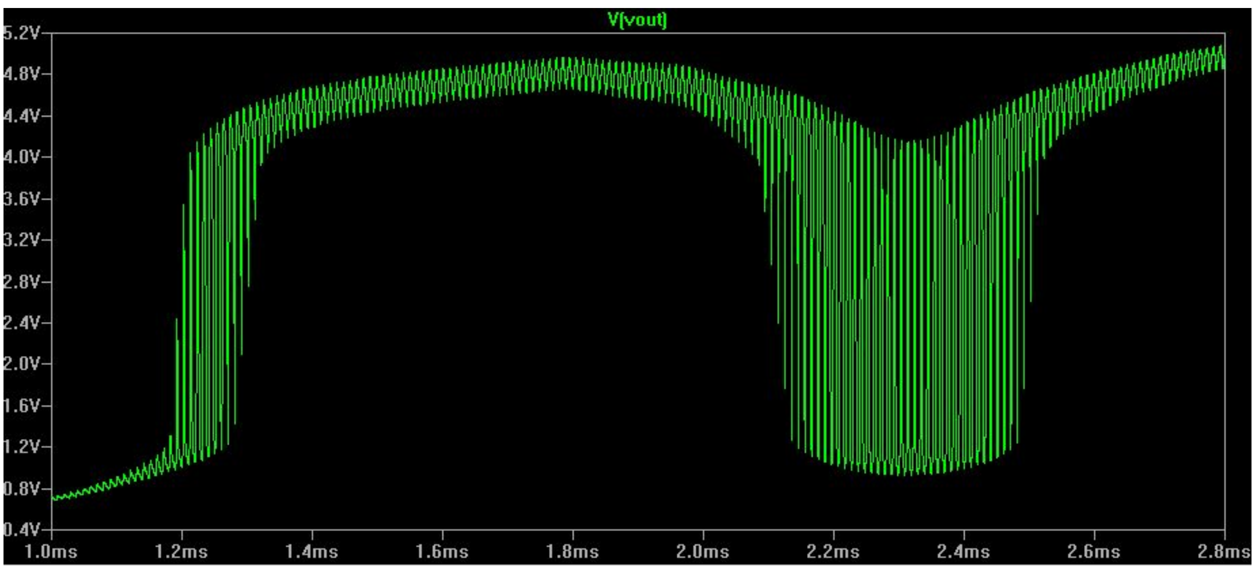


Figure 11: LTSpice simulation output, with just Vout displayed: Frequency = 526.3Hz ~ 98.7Hz - 98.2kHz

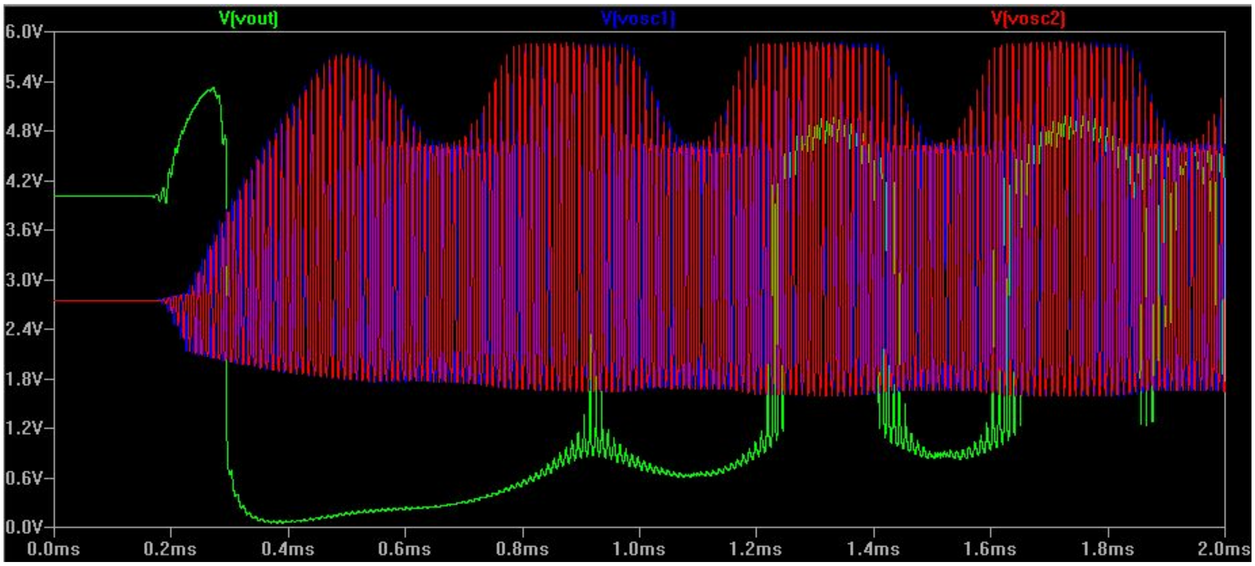


Figure 12: LTSpice simulation output with variable inductor at 2.1mH: frequency in output.

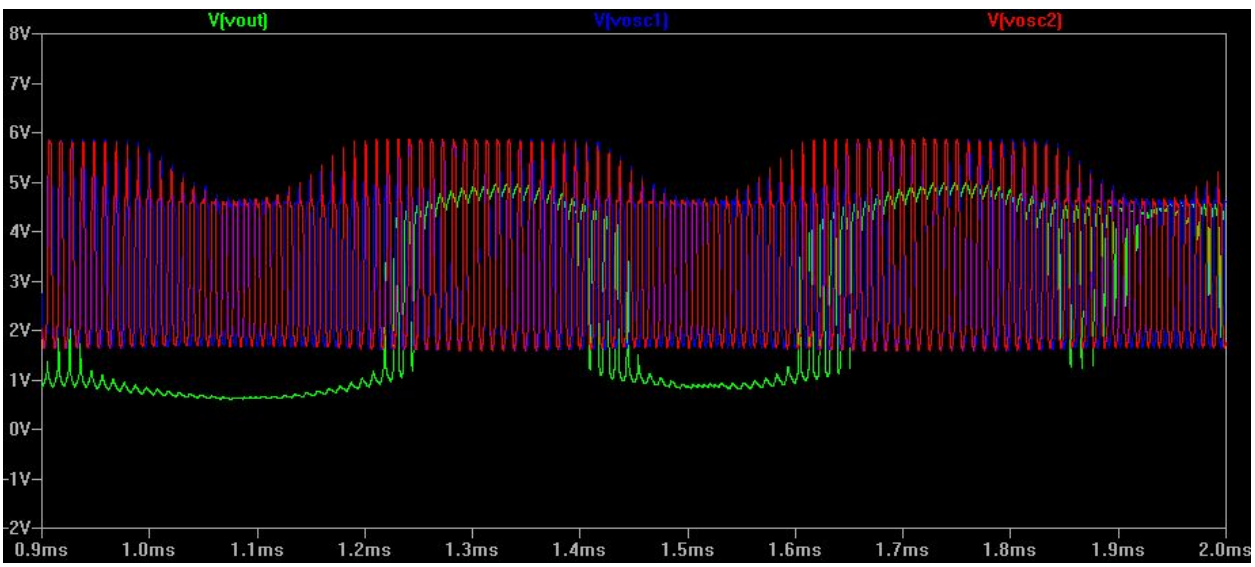


Figure 13: LTSpice simulation output, with just Vout displayed: Frequency = 2.38kHz ~ 98.7Hz - 96.3kHz

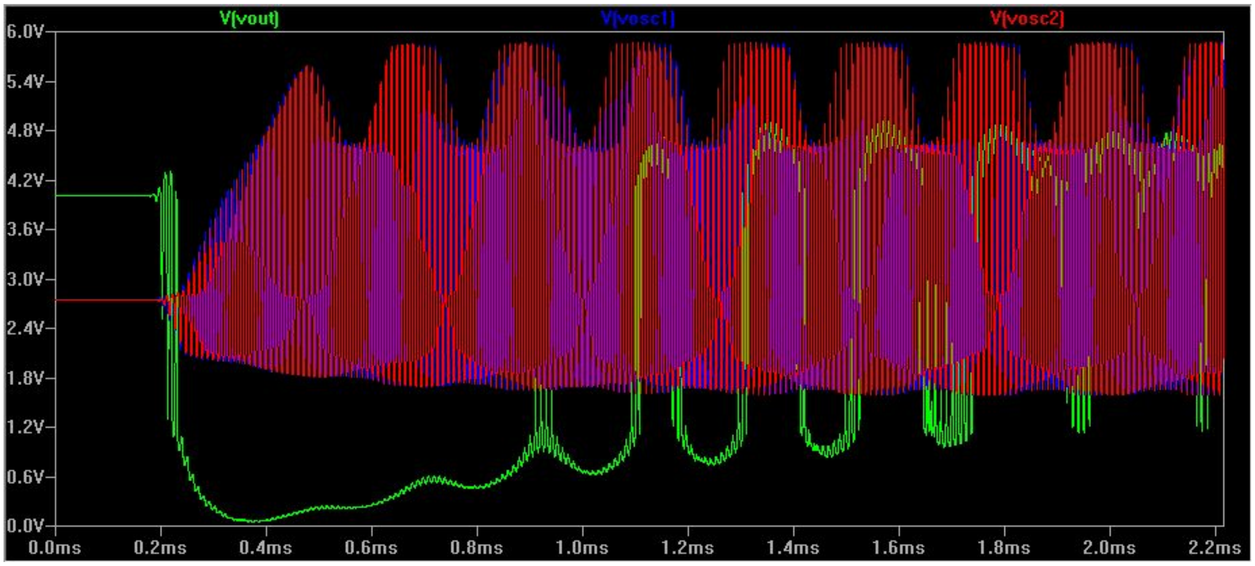


Figure 14: LTSpice simulation output with variable inductor at 2.2mH: frequency in output.

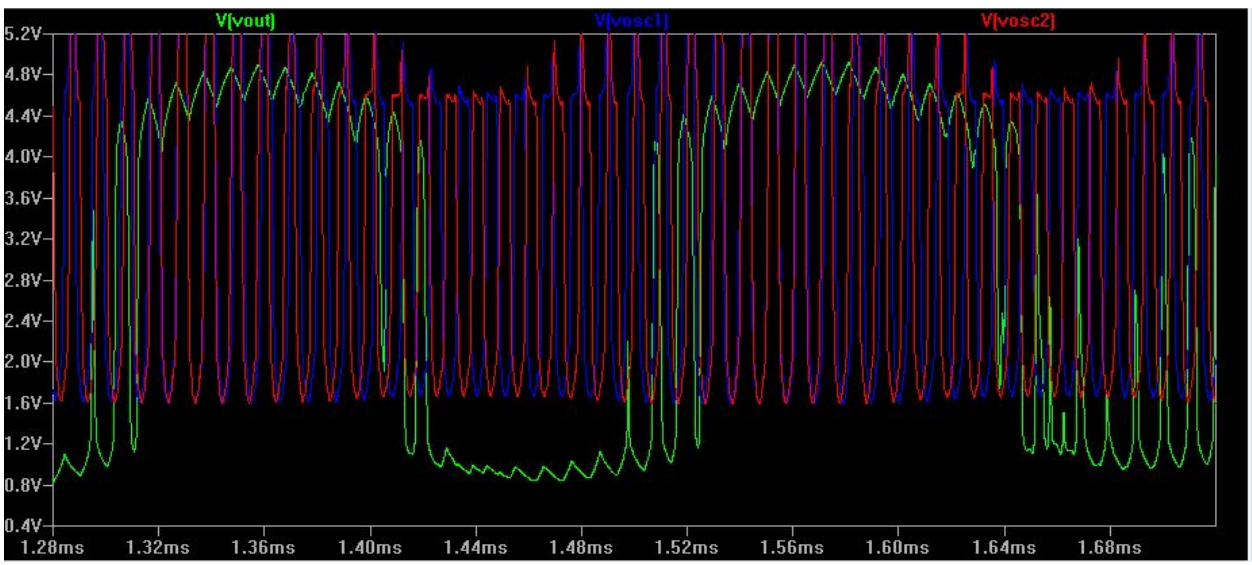


Figure 15: LTSpice simulation output, with just Vout displayed: Frequency = 4.35kHz ~ 98.7Hz - 94.2kHz

Stage 3: Output stage:

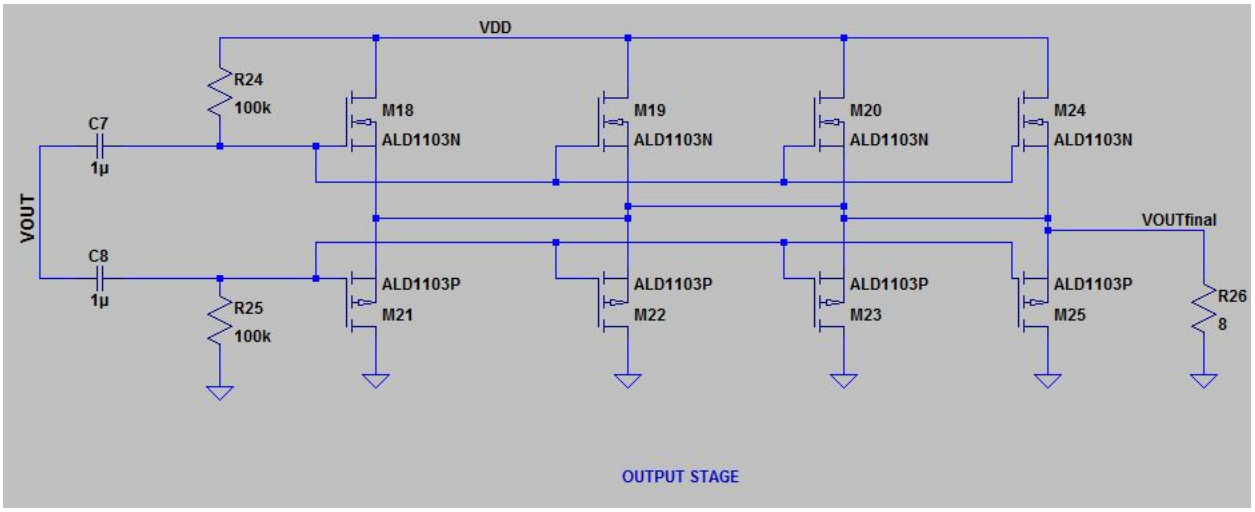


Figure 16: LTSpice schematic for output stage.

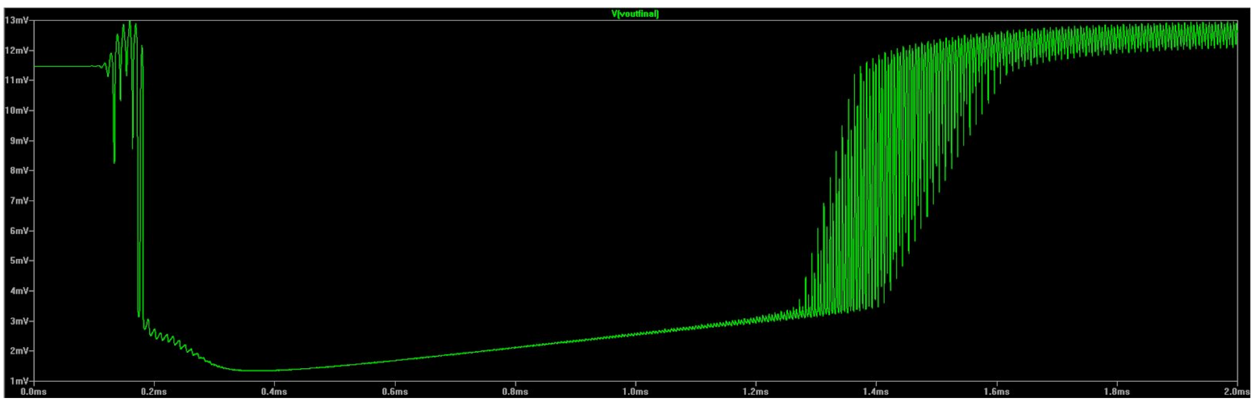


Figure 17: LTSpice simulation for output stage, with both oscillators producing 100kHz.

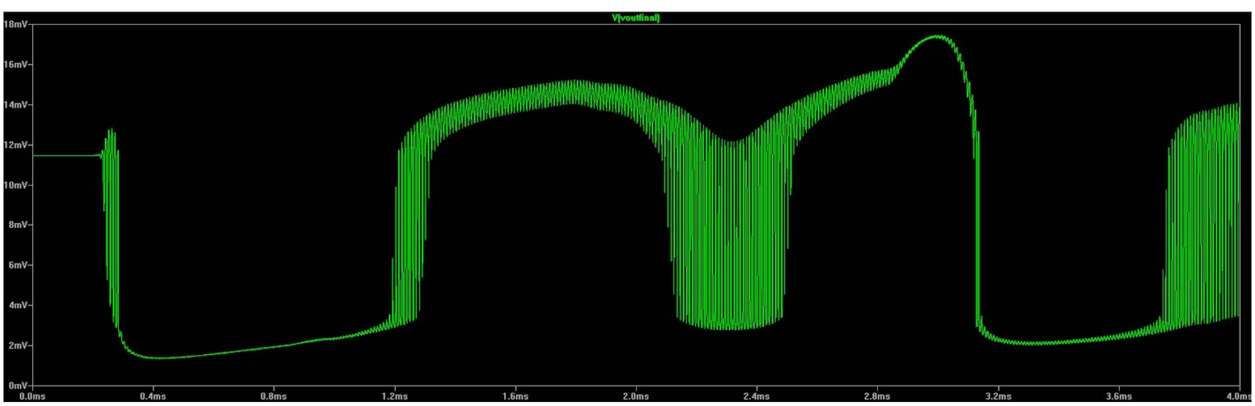


Figure 18: LTSpice simulation for output stage, with one oscillator at 1% inductance difference.

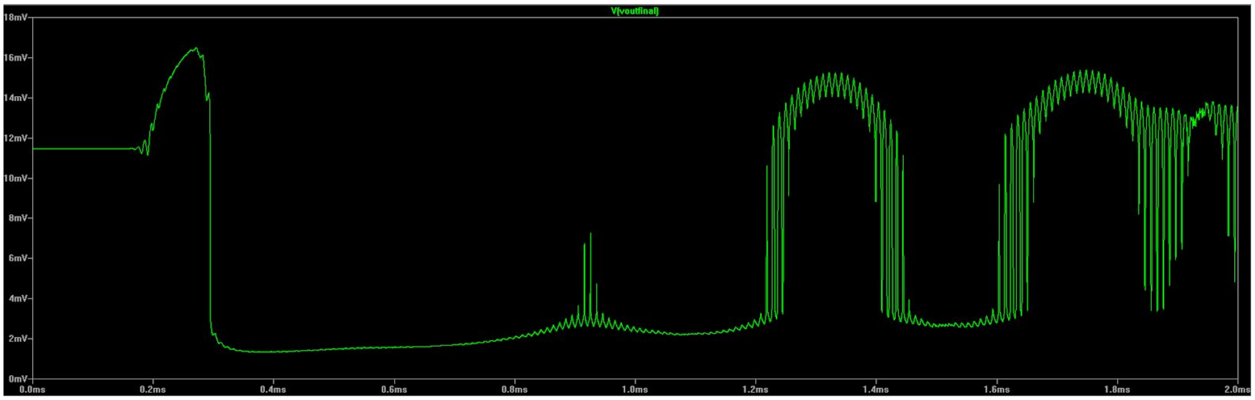


Figure 19: LTSpice simulation for output stage, with one oscillator at 5% inductance difference.

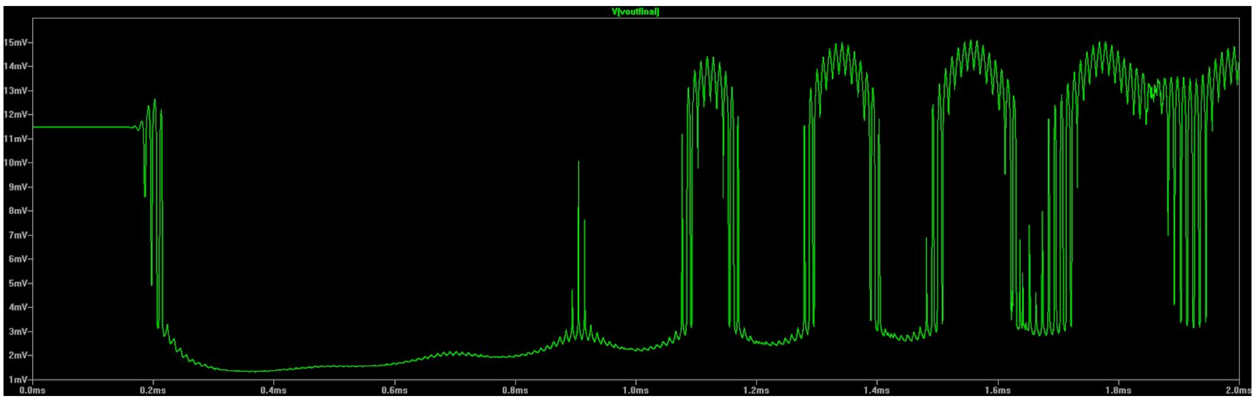


Figure 20: LTSpice simulation for output stage, with one oscillator at 10% inductance difference.

PCB Layout

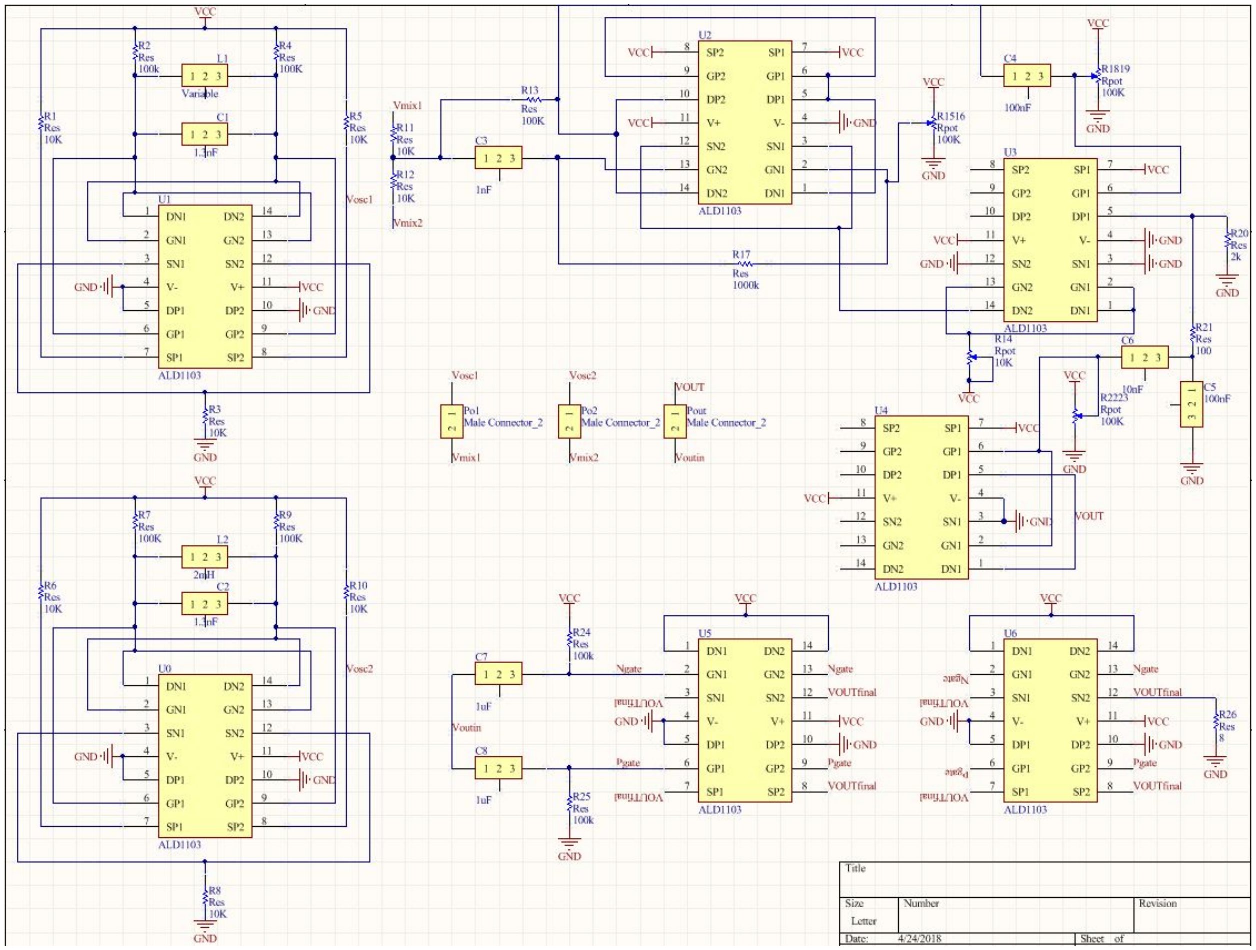


Figure 21: Overall Altium PCB Schematic for metal detector.

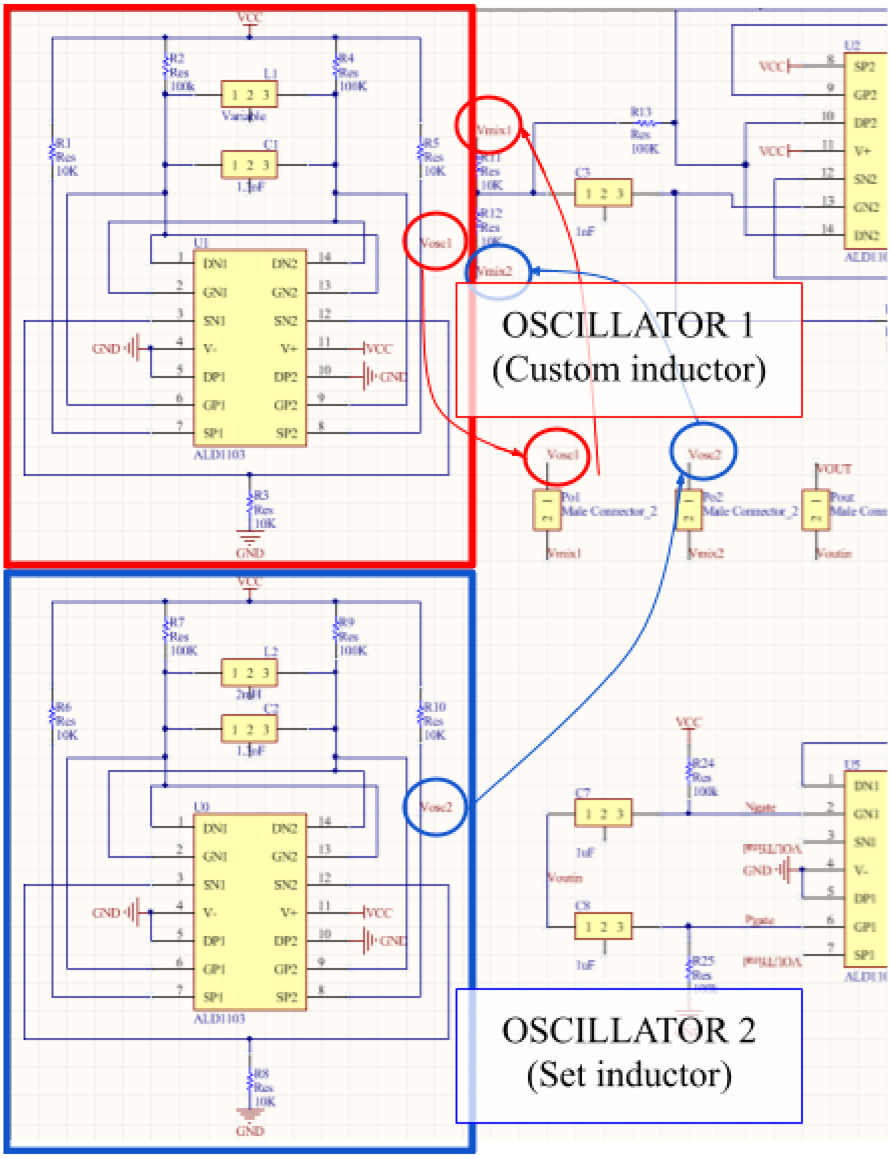


Figure 22: Altium PCB Schematic: Oscillators, with outputs Vmix1 and Vmix2 labelled.

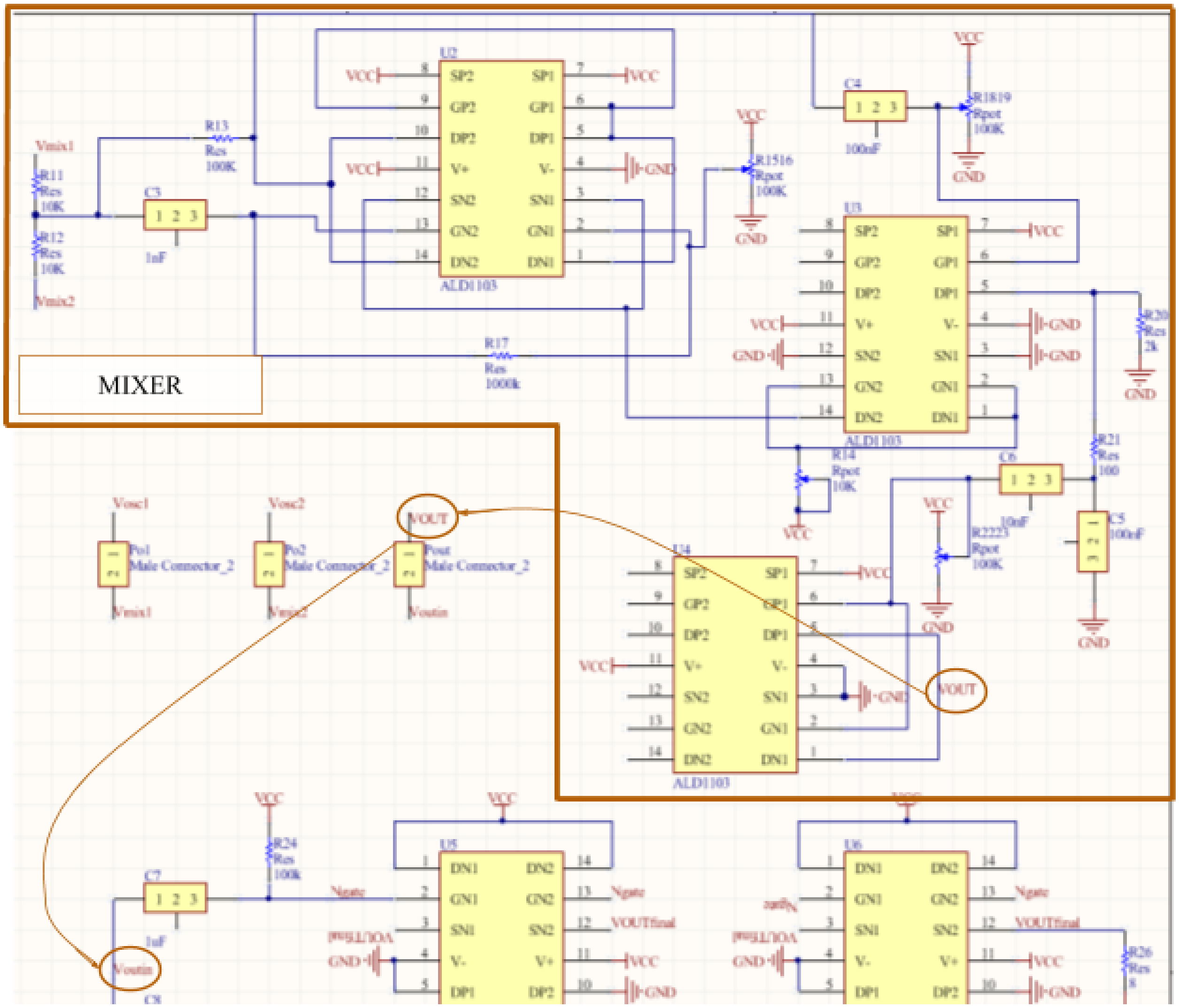


Figure 23: Altium PCB Schematic: Mixer, with output VOUT labelled.

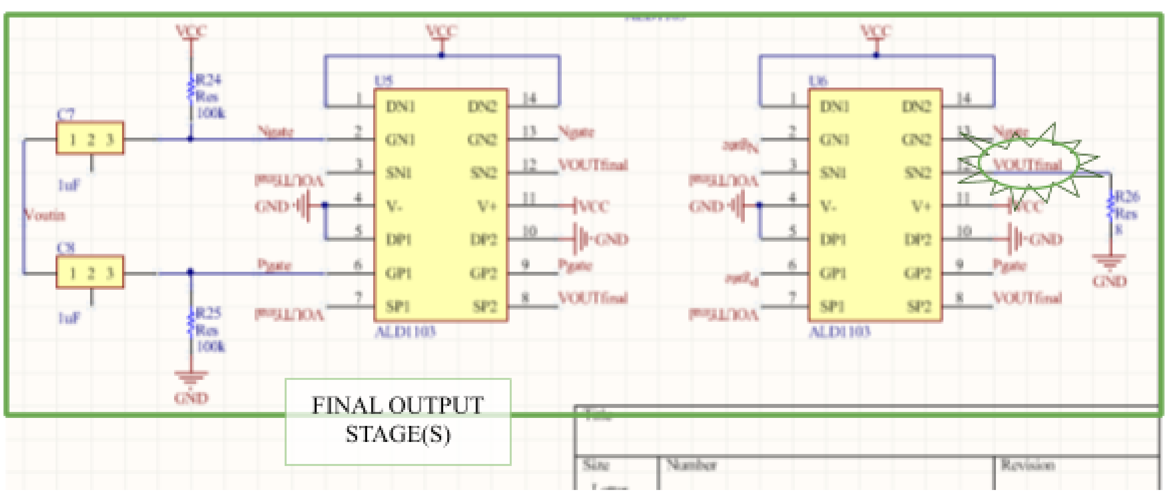


Figure 24: Altium PCB Schematic: Output stage, with output VOUTfinal labelled.

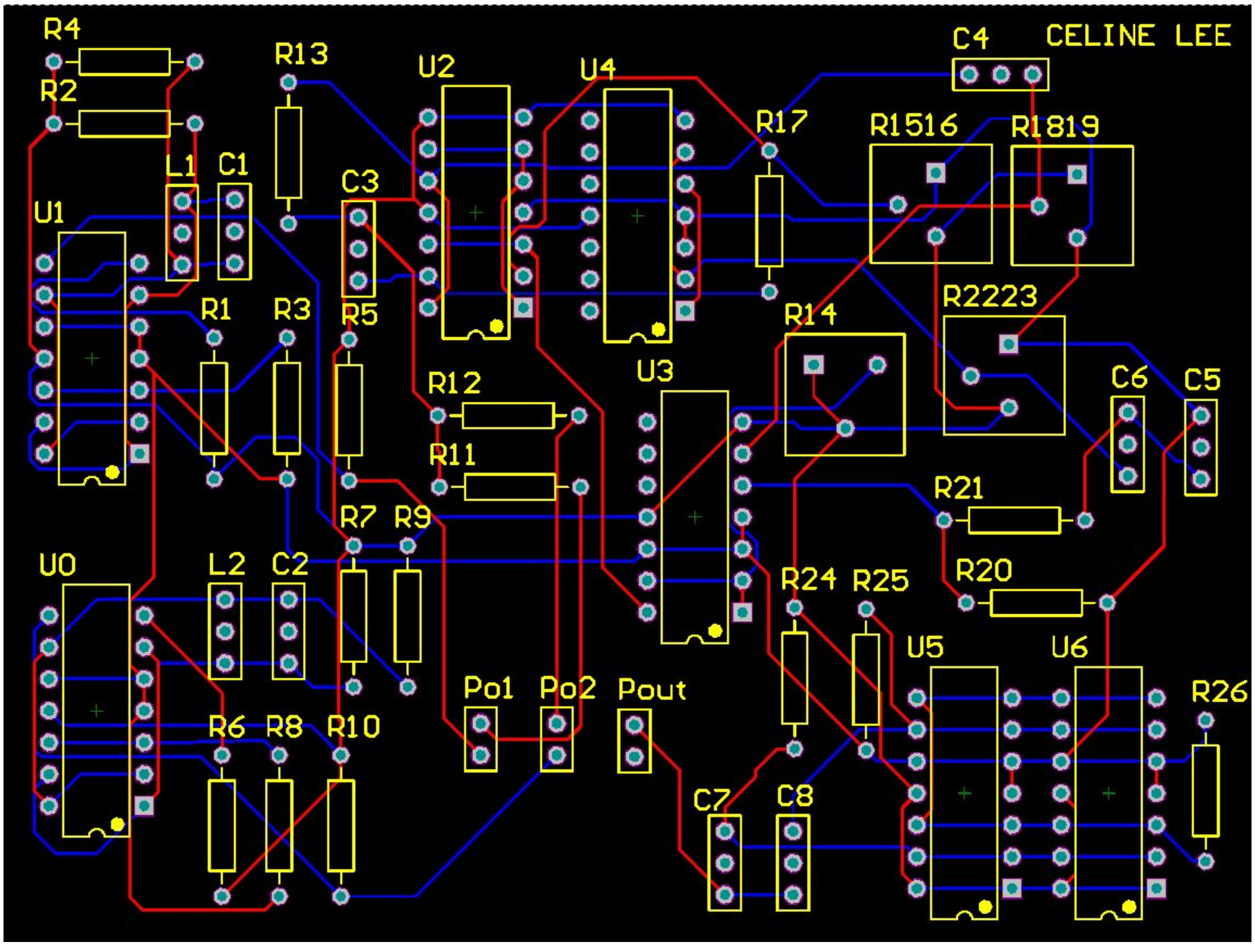


Figure 25: Altium PCB board layout, with components labelled correspondingly to PCB schematic.

Measurement Results

Measurement procedure:

1. Remove caps from male-male headers.
2. Power the board by attaching the battery positive terminal to VCC, ground terminal to GND.
3. Hook up the oscilloscope. Attach BNC-to-grabber cables to channels 1 and 2.
4. Measure the oscillator:
    a. Attach the ground terminal to the GND of the PCB. Attach the positive terminal to the Vosc1 for channel 1, and Vosc2 for channel 2.
    b. Measure frequency and collect results. One with both as 2mH inductors, one with the inductor for oscillator 1 replaced by the custom inductor.

5. Remove the cable for channel 2.
6. Measure the mixer:
    a. Generate two waveforms: both 500mVpp, one set at 100kHz, and the other available for modification (call this wave X).
    b. Connect the set 100kHz wave to Vmix1 and X to Vmix2.
    c. Connect the oscilloscope cable to VOUT. Measure results for X = 100kHz, 102kHz.
7. Measure the output stage:
    a. Attach cable between VOUT and Voutin.
    b. Connect oscilloscope cable to Voutfinal. Measure results for X = 100kHz, 102kHz.
    c. Attach speaker. Make sure it plays.
8. Measuring it all together:
    a. Attach the custom inductor to the inductor slot for oscillator 1.
    b. Re-attach male header caps between Vosc1 and Vmix1, Vosc2 and Vmix2, and VOUT and Voutfinal.
    c. Test the metal detector with the speaker.

<u>Measurement results:</u>

After oscillator:

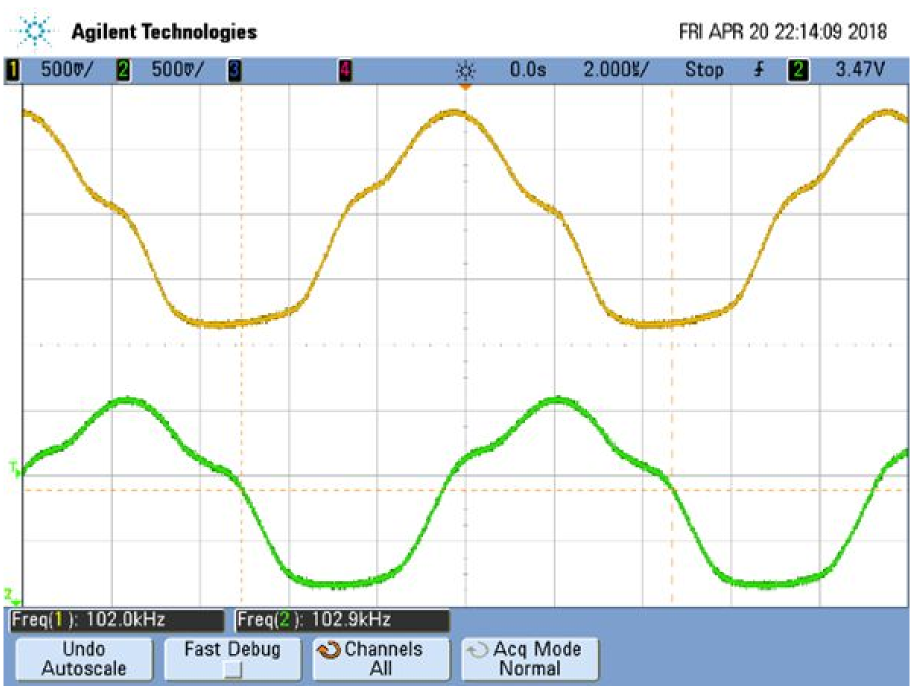


Figure 26: After oscillator stage, both with 2mH inductors. Channel 1: Vosc1; Channel 2: Vosc2.

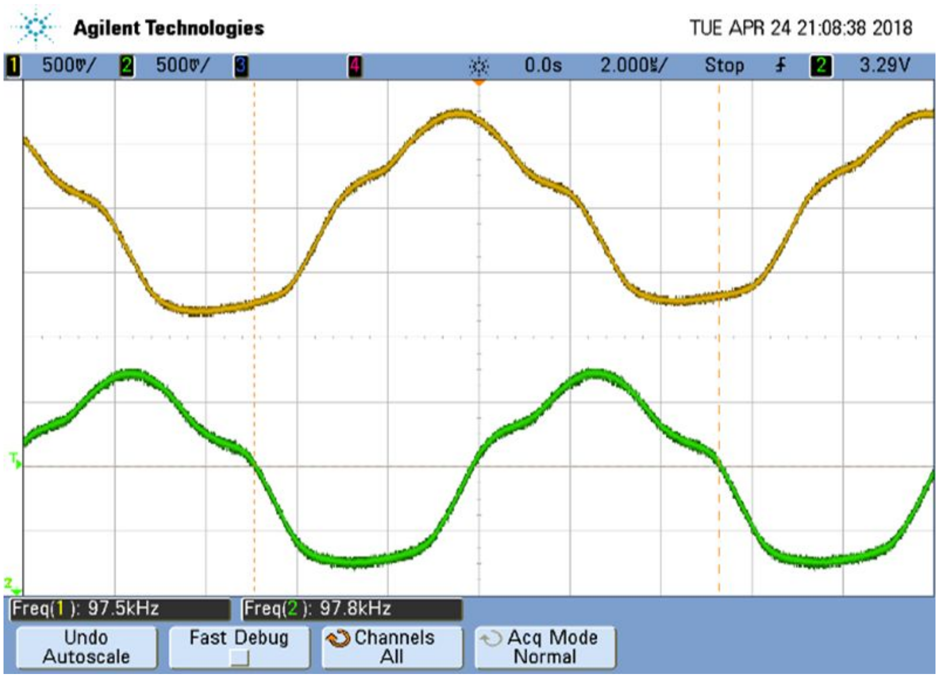


Figure 27: After oscillator stage, with 2mH inductor in Vosc2 and custom inductor in Vosc1. Channel 1: Vosc1; Channel 2: Vosc2

After mixer:

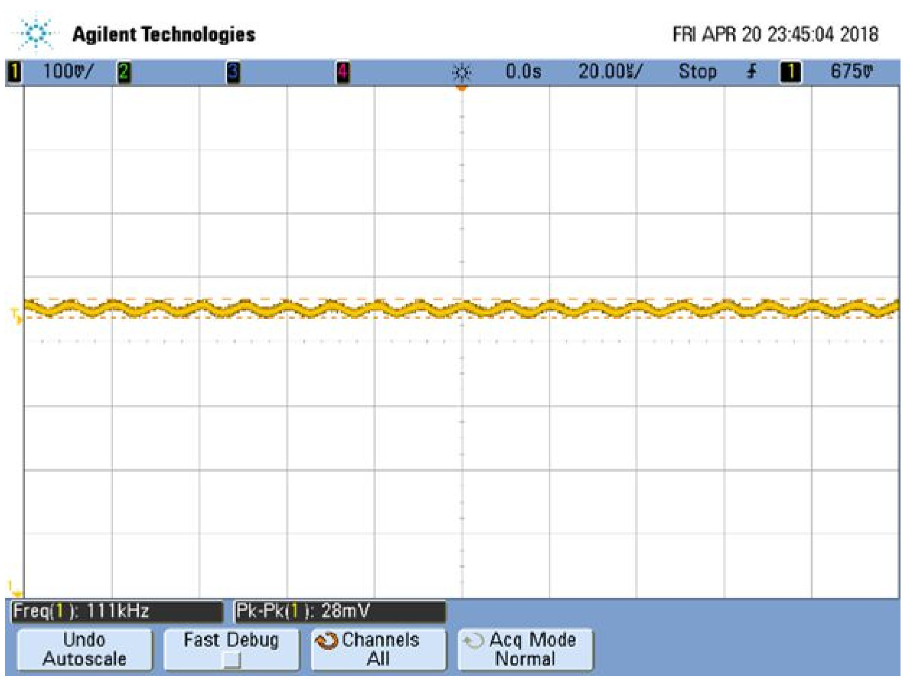


Figure 28: After mixer stage, with both Vmix1 and Vmix2 as 100kHz. VOUT has null oscillation.

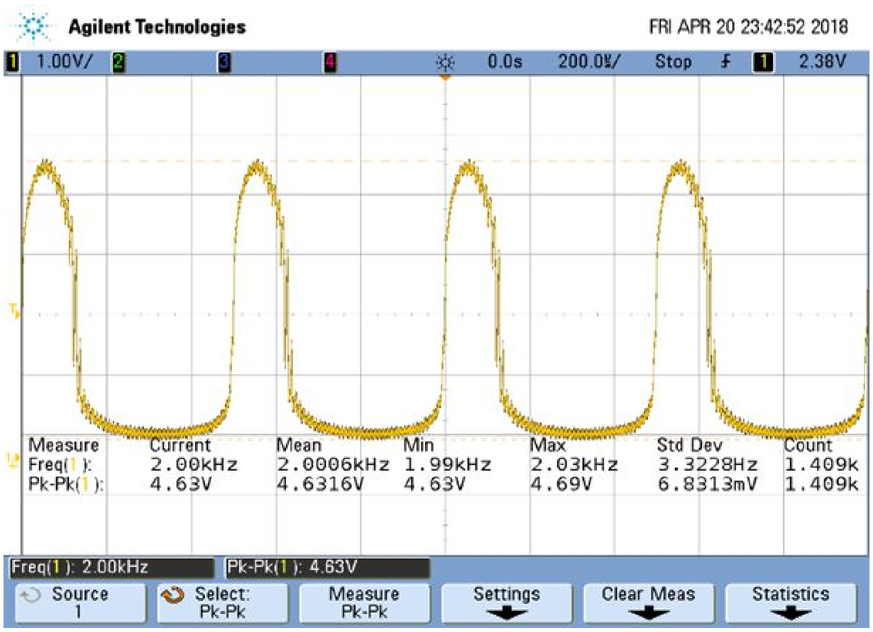


Figure 29: After mixer stage, with Vmix1 as 100kHz and Vmix2 as 102kHz. VOUT is 2kHz.

After output stage:

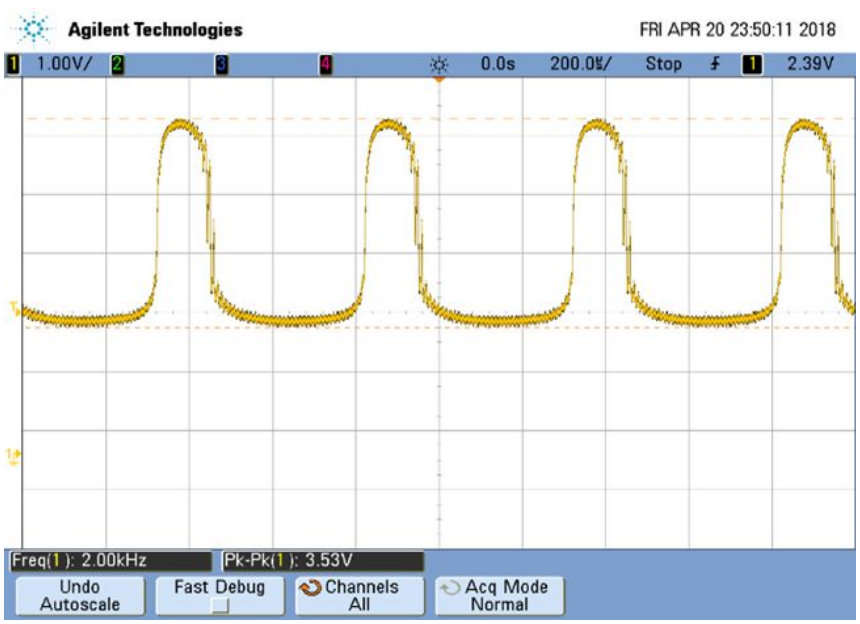


Figure 30: After output stage, with Vmix1 as 100kHz and Vmix2 as 102kHz. VOUT is 2kHz, and a smaller pk-pk value than after the mixer.

Put all together:

The metal detector effectively detected metal! See the discussion and conclusion for further analysis.

Experimental results did meet design requirements. Isolated components worked as intended, even when measured on the oscilloscope, and when put together the entire metal detector functioned (almost) perfectly.

Discussion

Table 1: Summary of major data results

	Simulated	Calculated	Measured
Frequency	98700Hz	98703Hz	97800Hz
Custom inductance	N/A	1.990mH	1.98mH
Gain	0.35	1	0.76

The measurements, calculations, and simulations for the project as a whole were pretty consistent with one another. The metal works better (is more sensitive) with closer-matching produced frequencies out of the oscillator. Any discrepancy between theory, where we design a perfect LC oscillator duo to produce identical frequencies, and physical results, is due to imperfection of produced parts and rounding in calculations. After the metal detector was put together with the calculated values, I did proceed to empirically tune each component in order to better each element of the project. This process of ball-parking the range of values for each component, then fine-tuning experimentally, worked well in creating an effective metal detector.

Conclusion

Overall, the final project was executed smoothly. Individual components functioned as desired, based on LTSpice schematics. I am very glad that I did spend time to carefully build the circuit correctly on Altium, because adding components outside the PCB is hard work and requires a lot of precision as well as creativity. I did forget to add ports for power and for ground, so I had to find appropriate slots to solder in power and ground wires. Also, it was difficult to make the oscillators produce perfectly equal frequency outputs because of discrepancies in the custom coil vs. the set inductor. It would have been easier to set the set inductor first, then add/remove coils to/from the custom coil appropriately, because that would be finer tuning, but I cut the coil before I could make the appropriate modifications. As a result, the metal detector did make some noise even when it was not detecting any metal. Sometimes, when it detected metal from a certain distance, rather than increase frequency of the signal, it would go to make no noise, when the inductance of the custom coil did move toward the desired inductance. Aside from this slight imperfection, however, the metal detector project was excellent. The PCB was placed close enough to the custom coil so that the wires did not reduce inductance too much, and the battery was placed high, by the hand, to maintain physical balance for the stick. Also, it did work as a metal detector, so success!