Lab 10: Metal Detector

Panos Dimtsoudis
ESE 3190, University of Pennsylvania
5/12/2026
Instructor: Dr. Thomas Farmer

Intro

The goal of this project was to design, simulate, build, and test an analog metal detector that produces an audible response when metal is brought near the sensing coil. The circuit is based on two LC oscillator stages: one fixed oscillator and one variable oscillator. The fixed oscillator uses a shielded inductor to keep its frequency relatively constant, while the variable oscillator uses a custom unshielded inductor whose inductance changes when nearby metal induces eddy currents. This change in inductance shifts the variable oscillator frequency, creating a frequency difference between the two oscillators.

The outputs of the two oscillators are then combined in a mixer stage, producing a lower-frequency beat signal equal to the difference between the oscillator frequencies. This signal is passed through common-source amplifier stages and filtering before driving the output speaker. In this way, a change in the magnetic environment around the custom inductor is translated into a change in the audible output of the circuit. The project therefore combines several core analog building blocks from the course, including LC oscillators, differential/mixer behavior, biasing, common-source amplification, filtering, PCB layout, LTspice simulation, and oscilloscope testing.

In this report, I present the design strategy, hand calculations, LTspice simulations, PCB layout, and experimental measurements for the complete metal detector. The current report already includes the simulated oscillator, mixer, and output-stage results, as well as the fabricated PCB layout and oscilloscope measurements of the main circuit nodes, so the introduction should frame the report as a comparison between the intended design behavior, simulated behavior, and measured hardware performance.

Design Strategy

The design strategy for this metal detector was to build the circuit as a sequence of analog stages: two LC oscillators, a mixer/summing stage, gain and filtering stages, and an output stage to drive the speaker. The fixed oscillator was designed to stay close to 50 kHz, while the variable oscillator was designed to be slightly lower, around 49 kHz, so that the mixer would produce an audible beat frequency equal to the difference between the two oscillator frequencies. This follows the project requirement that one oscillator use a fixed 10 mH inductor and the other use the measured custom inductor value, with capacitor values chosen to place the two oscillation frequencies near 50 kHz and 49 kHz.

For the custom inductor, I chose an inductance value in the allowed 5 mH to 10 mH range because this range can create a working oscillator and can be tuned with the LC tank capacitor. In my simulation, the custom inductor was set to approximately 7.5 mH, and the capacitor in the variable oscillator tank was chosen to make the oscillator run near 49 kHz. The fixed oscillator used a 10 mH inductor with a capacitor chosen to run near 50 kHz. These values were selected using the LC oscillator relationship $f = \frac{1}{2\pi\sqrt{LC}}$, then adjusted in LTspice so the simulated oscillator frequencies matched the target values. In the current report schematic, the simulated custom oscillator uses L=7.5 mH and C=1.41 nF, while the fixed oscillator uses L=10 mH and C=0.99 nF.

The resistor values were chosen based on biasing, gain, and loading requirements for each stage. In the oscillator stages, the resistors provide the proper DC operating points while allowing the LC tank to oscillate without being overly loaded. In the mixer stage, the two oscillator outputs are combined through equal input resistors so that the fixed and variable oscillator signals contribute similarly to the mixed signal. The mixer biasing resistors and current-mirror/tail-current network were chosen so that the MOSFETs operate in saturation during normal operation, since leaving saturation would introduce extra nonlinearity and reduce predictable mixing behavior. The use of tunable bias points is important because the real PCB circuit can differ from the ideal LTspice model due to transistor variation, parasitic resistance/capacitance, and inductor tolerance.

For the amplifier and filter stages, the bias points were chosen to give enough voltage swing without clipping while still providing gain. The common-source amplifier gate bias was set using a resistor divider so that the transistor would remain in saturation around its DC operating point. The source/load resistor values were then chosen to control the gain and output swing. The RC low-pass filter was placed after the first gain stage to reduce the high-frequency oscillator components while keeping the lower-frequency beat signal that should be heard by the speaker. In my schematic, the filter uses R=100Ω and C=100 nF, giving a cutoff frequency of about 15.9

kHz, which is low enough to attenuate the 50 kHz carrier but high enough to pass the audible beat signal.

Finally, the output stage was designed to drive the low-resistance speaker/load without connecting the earlier common-source stage directly to the speaker. The speaker is an 8Ω load, so it requires more current than the small-signal amplifier stages can safely provide. For that reason, the output stage uses coupling capacitors and a driver transistor stage so that the signal can be delivered to the speaker while keeping the DC biasing of the earlier stages separate from the speaker load. Overall, each component value was selected first from hand calculations, then refined in LTspice to make sure the oscillator frequencies, bias points, gain, filtering, and output waveform matched the intended metal-detector behavior.

Hand Calculations:

Prelab 10: Metal Detector

fixed Oscillator:

$f = \frac{1}{2\pi\sqrt{LC}}$, for $L = 10mH$, $f = 50kHz \rightarrow C \approx 1nF$

Variable Oscillator:

$f = \frac{1}{2\pi\sqrt{LC}}$, for chosen $L = 7.5mH \rightarrow C = 1.41nF$

Wired $L = 6.28mH$ thus $C \rightarrow 1.7nF$

Biasing Voltages

$V_B = V_{DD} \frac{R_2}{R_1 + R_2}$

Mixer: $R_{12} = 60k\Omega$, $R_{11} = 40k\Omega \rightsquigarrow V_B = 3V$

Oscillator: $R_1 = 100k\Omega$, $R_2 = 50k\Omega \rightarrow V_B = 5\frac{50}{100+50} = 1.67V$ (biased to 3V)

CS: $V_{G,CS1} = 5\frac{45}{15+45} = 3.75V$

$V_{SG1} = 1.25V$

$V_{G,CS2} = 5\frac{10}{50+10} = 0.833V$

$V_{SG2} = 5 - 0.833 = 4.17V$

CD: $V_G = 5\frac{100}{1.5+100} = 4.93V$

Curr Mirror:

$$I_{REF} = \frac{V_{DD} - V_{GS}}{R} = \frac{5-1}{100k\Omega} \Rightarrow I_{REF} \approx 40\mu A$$

$$I_{tail} = I_{REF} = 40\mu A$$

Gain Calculations:

Mixer: $A_{v,mix} \approx -\frac{R_F}{R_{in}} = -\frac{1M\Omega}{10k\Omega} = -100$

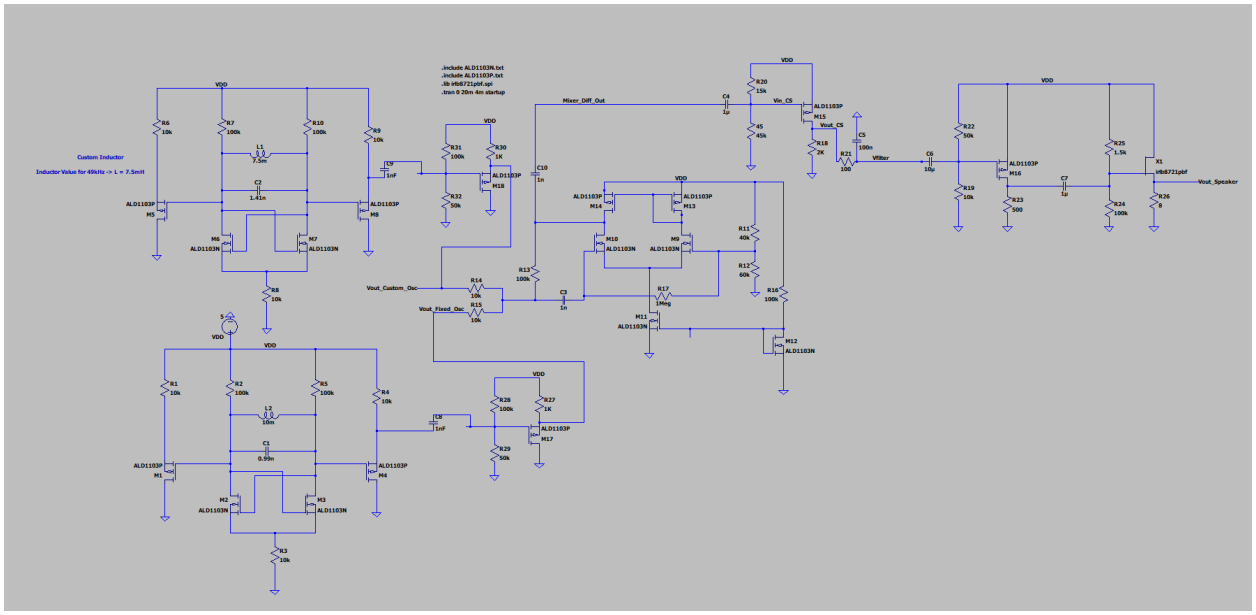
CS1: $A_v = -g_m(R_D \| r_o) \simeq -g_m R_D \approx -5\cdot10^{-3}\, 2\cdot10^{3} = -10\ V/V$

CS2: $A_v = (-5\cdot10^{-3})\,500 = -2.5\ V/V$

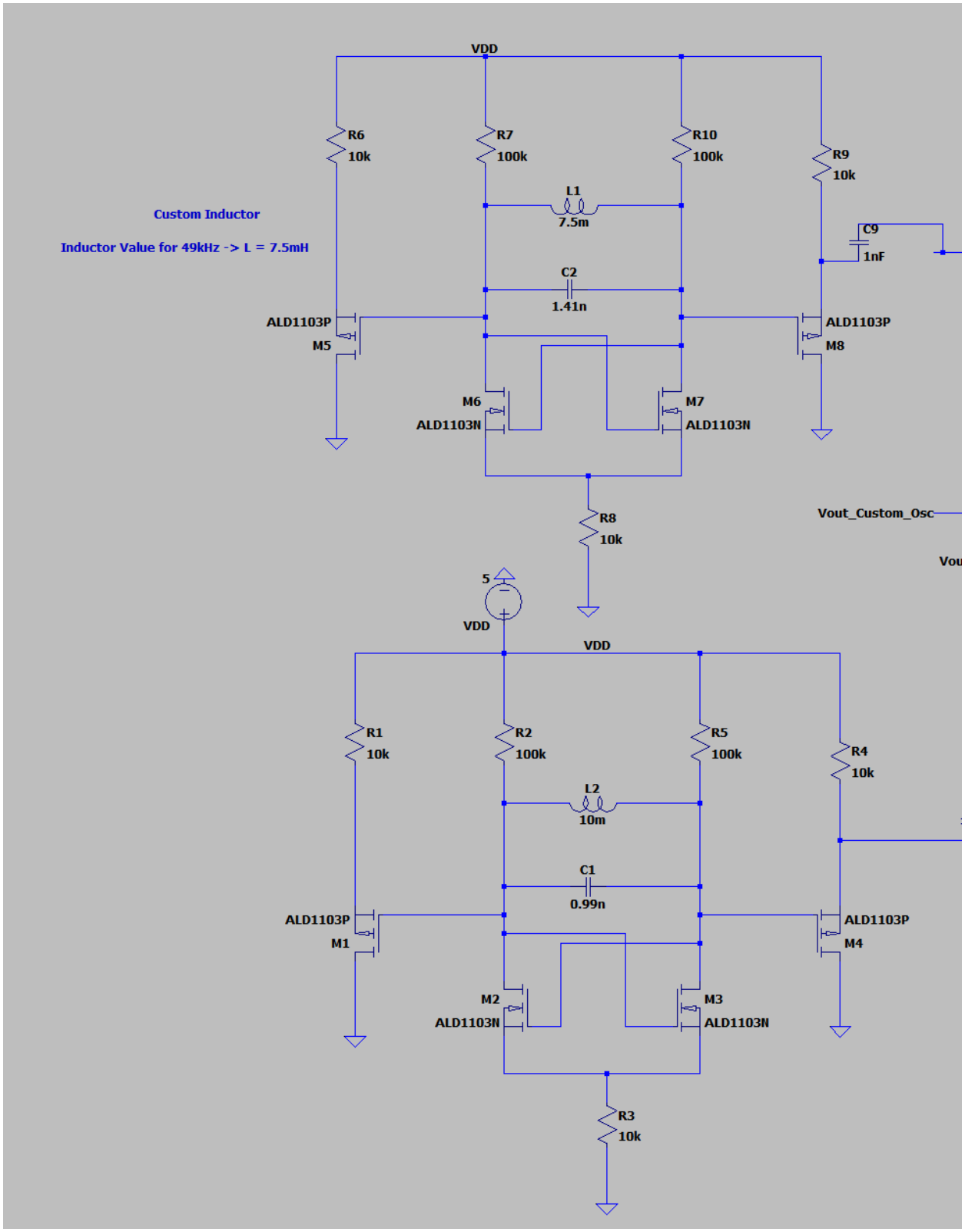
CD: $A_{v,CD} = \frac{g_m R_S}{1+g_m R_S} = \frac{5\cdot10^{-3}\cdot10^{3}}{1+5\cdot10^{-3}\cdot10^{3}} = 0.83$

LT Spice Simulations:

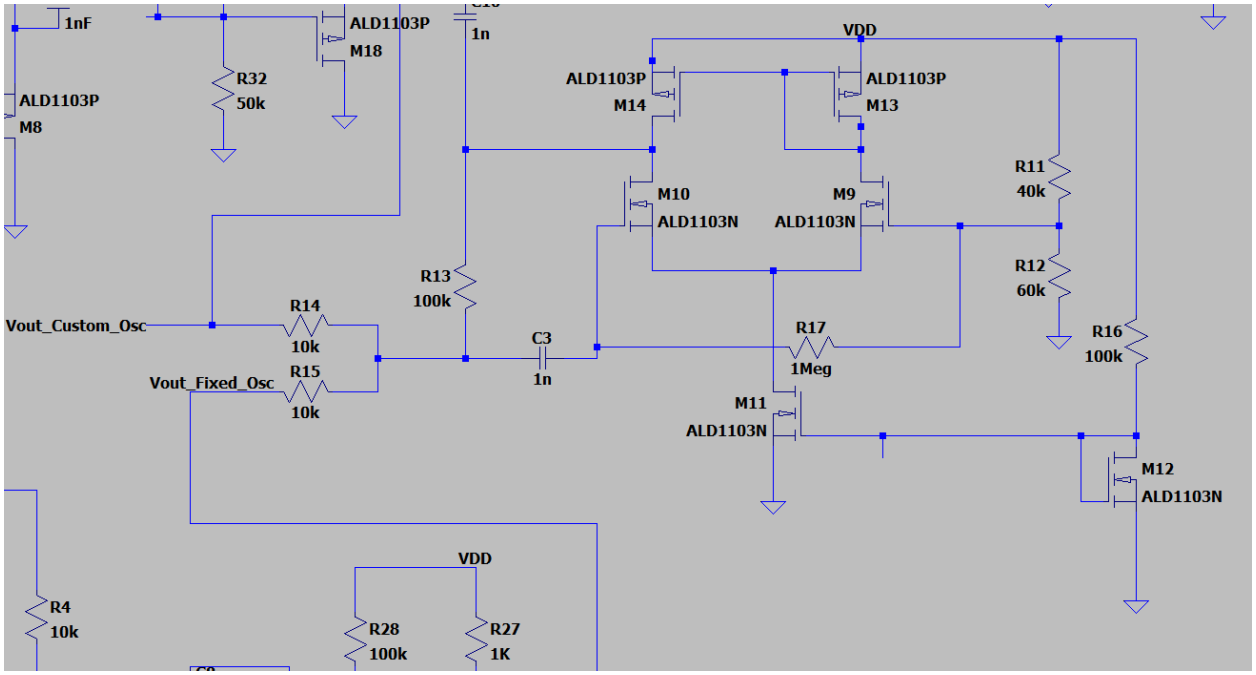
Full schematic:



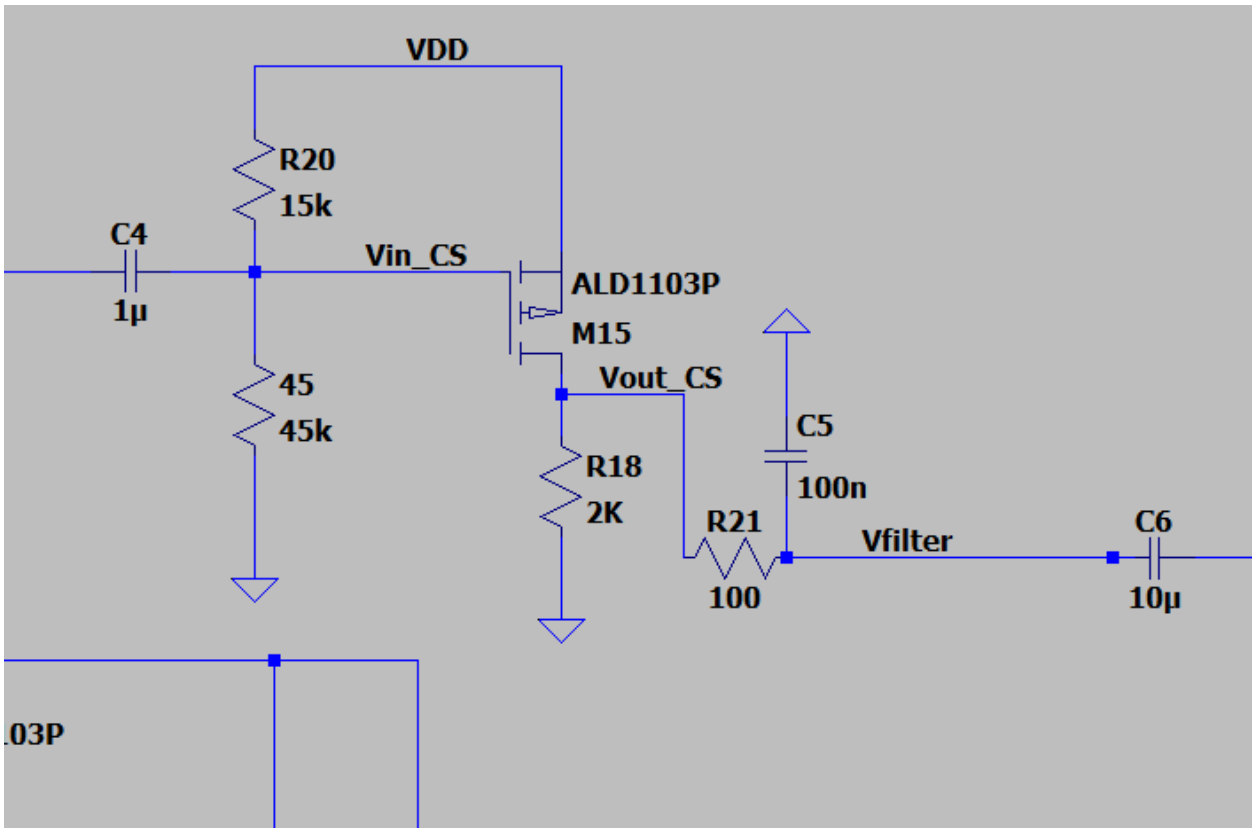
Oscillators:



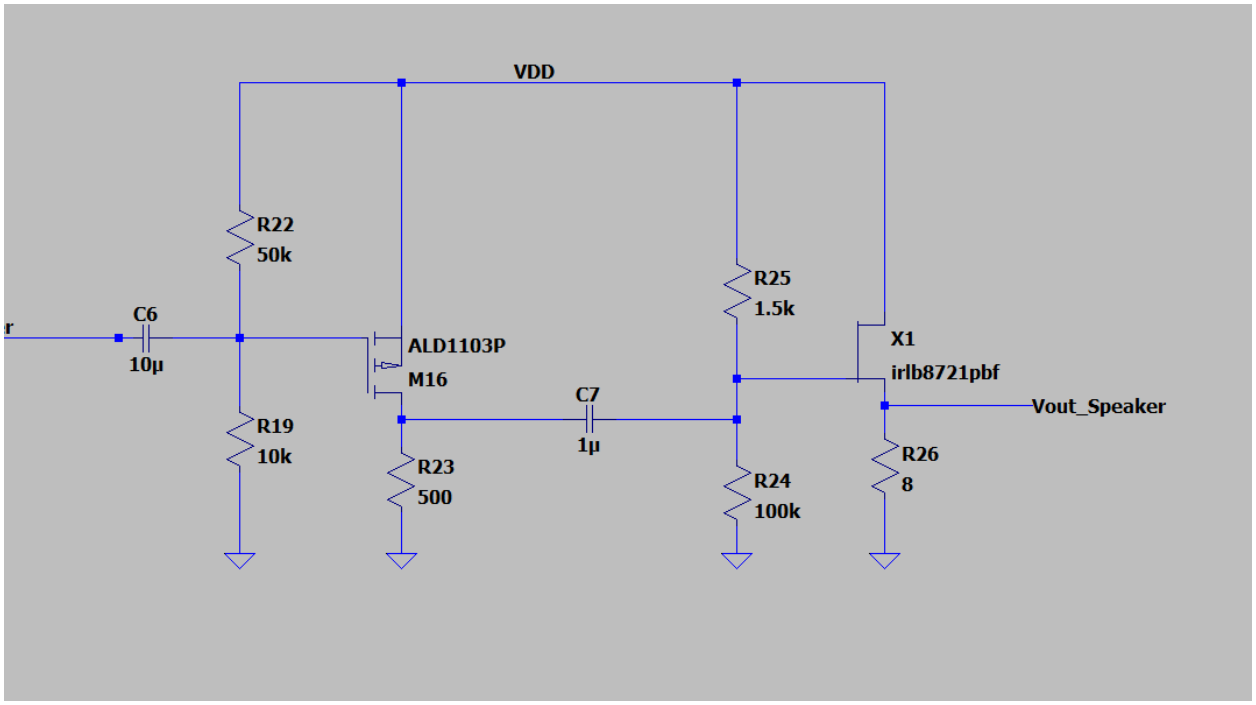
Mixer:


1nF
ALD1103P
M8
R32
50k
ALD1103P
M18
1n
VDD
ALD1103P
M14
ALD1103P
M13
R11
40k
M10
ALD1103N
M9
ALD1103N
R12
60k
R13
100k
Vout_Custom_Osc
R14
10k
C3
1n
R17
1Meg
R16
100k
Vout_Fixed_Osc
R15
10k
M11
ALD1103N
M12
ALD1103N
VDD
R4
10k
R28
100k
R27
1K

CS:

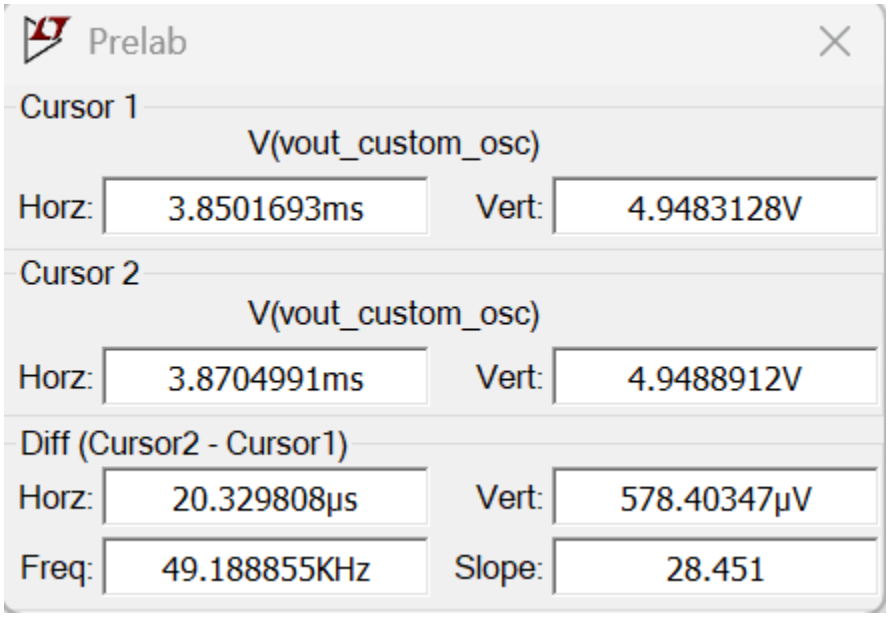

VDD
R20
15k
C4
1µ
Vin_CS
ALD1103P
M15
45
45k
Vout_CS
C5
100n
R18
2K
R21
100
Vfilter
C6
10µ
03P

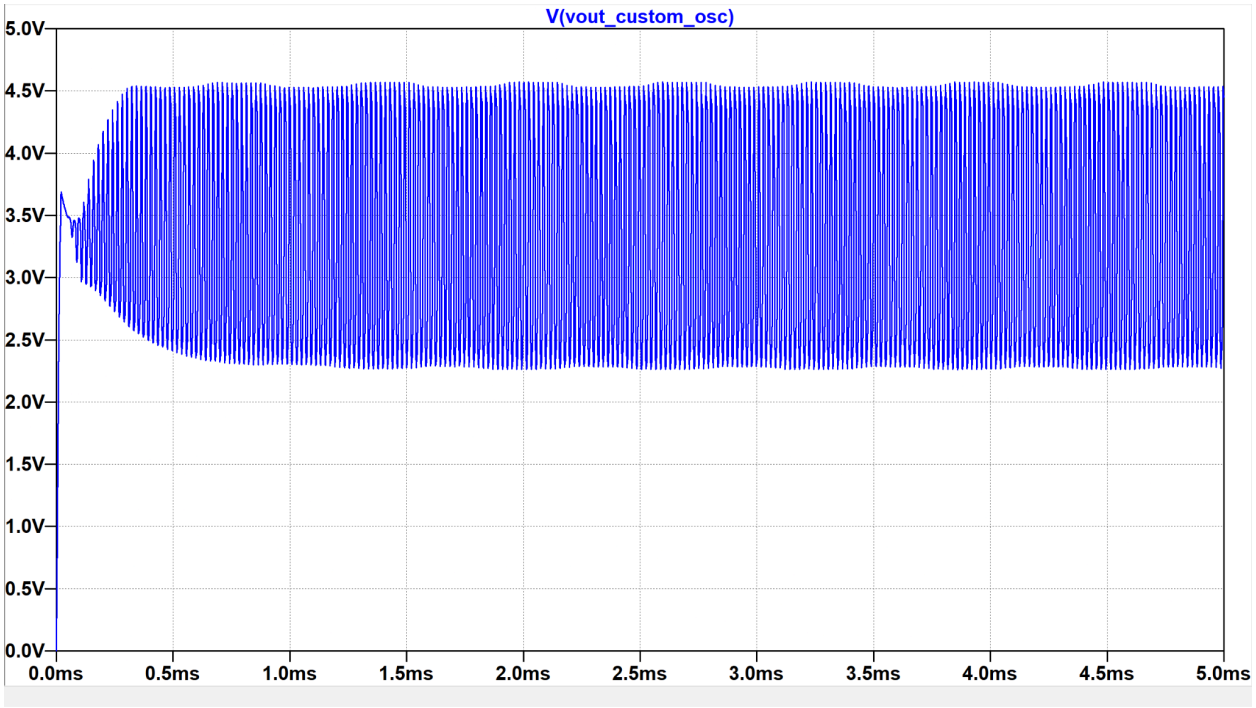
Output:


VDD
R22
50k
R25
1.5k
C6
10µ
ALD1103P
M16
X1
irlb8721pbf
C7
1µ
Vout_Speaker
R19
10k
R23
500
R24
100k
R26
8

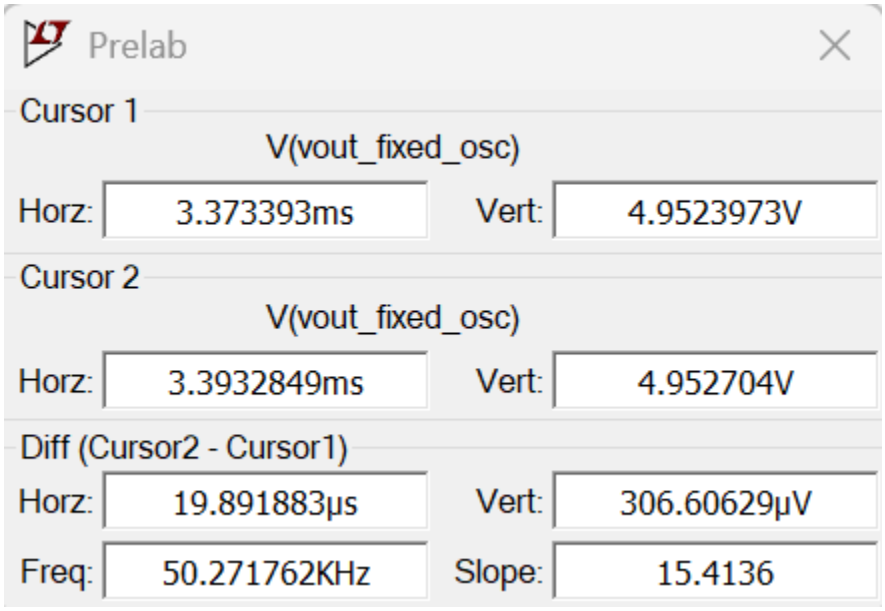
Simulation Results:

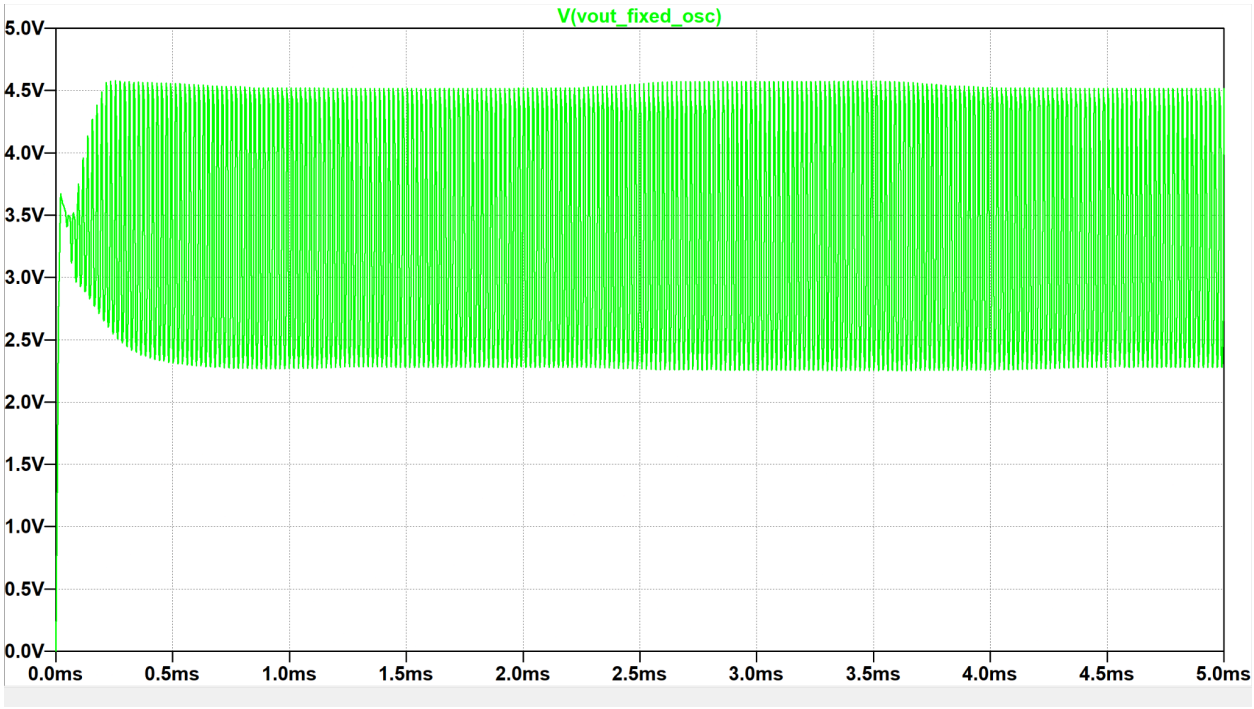
Variable Oscillator:



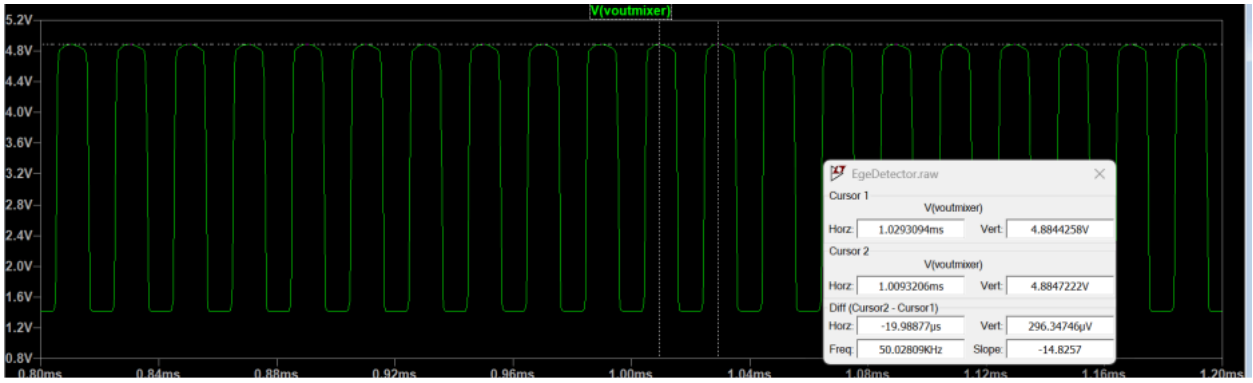


Fixed Oscillator:

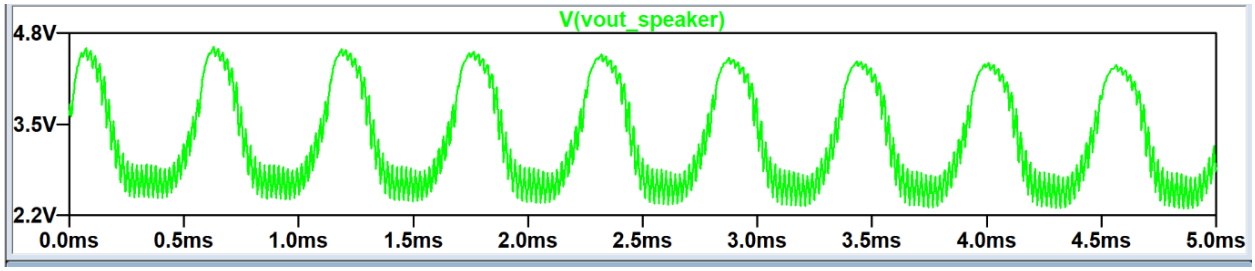


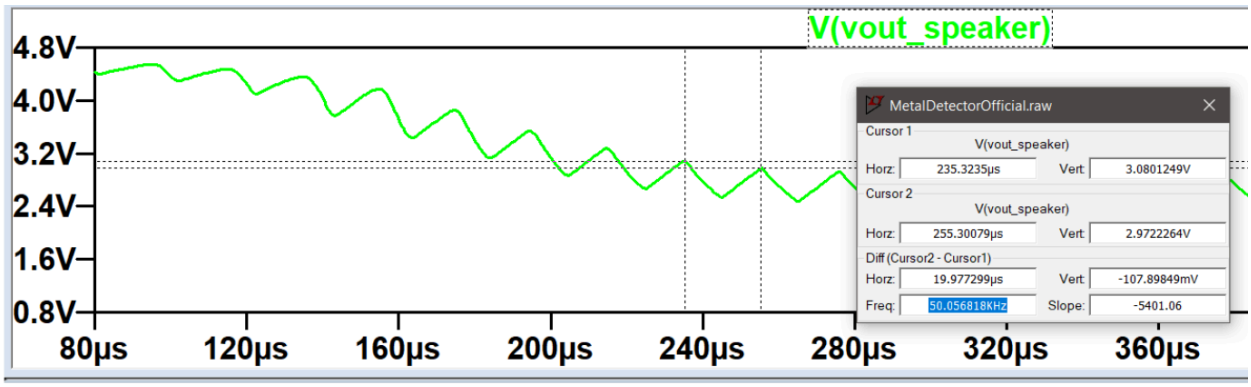


Mixer:

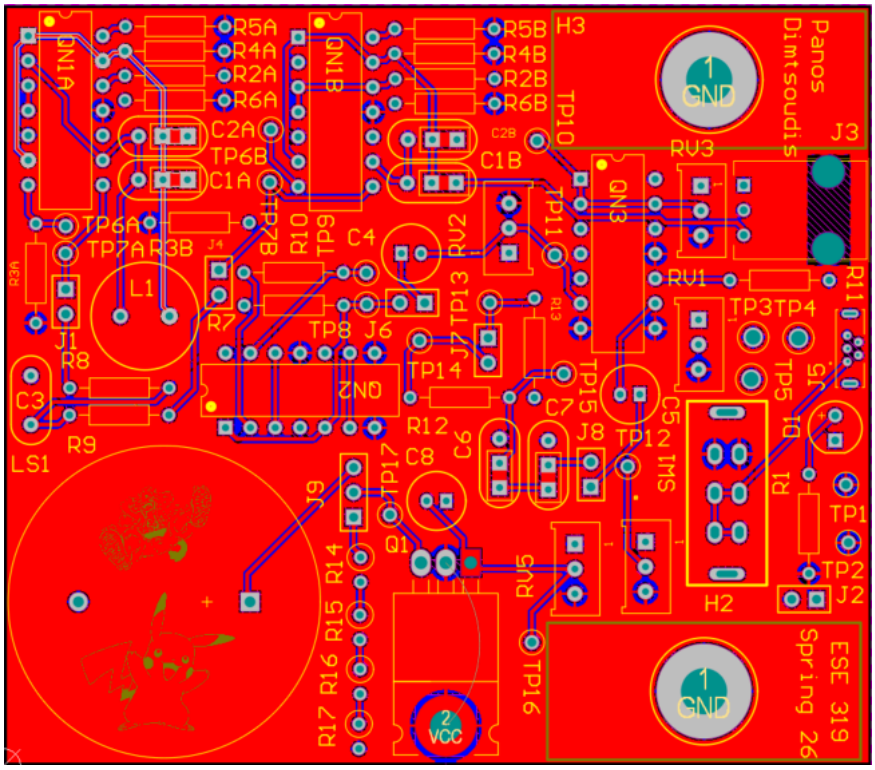


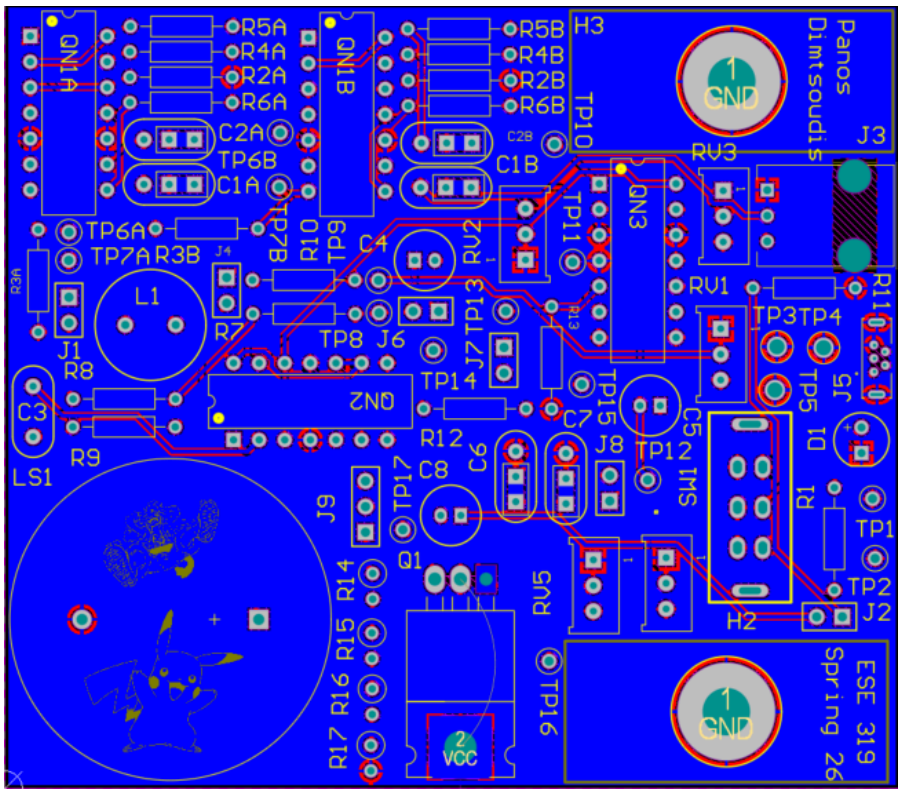
Speaker:

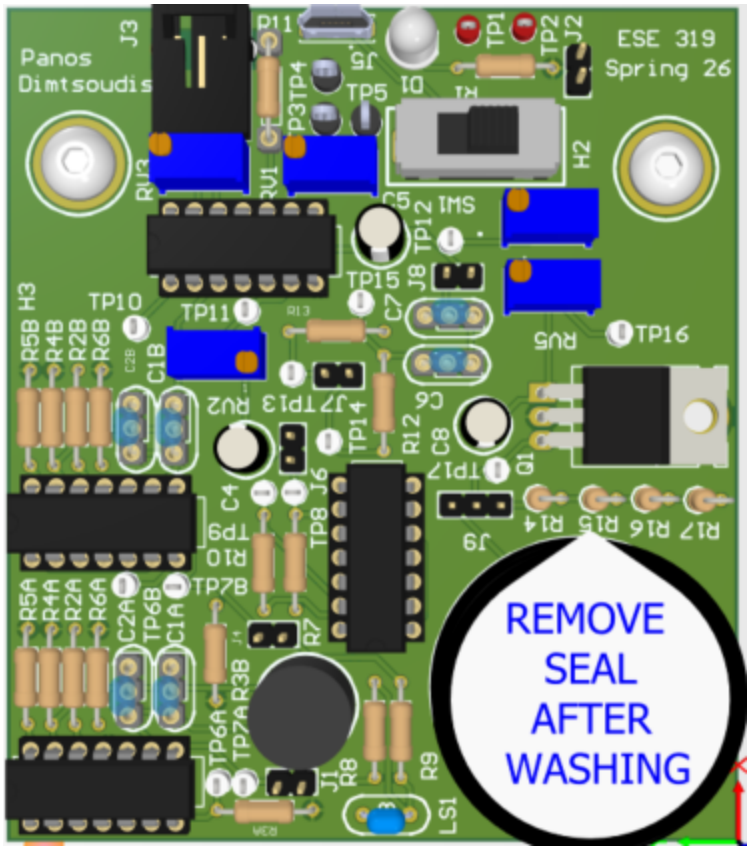


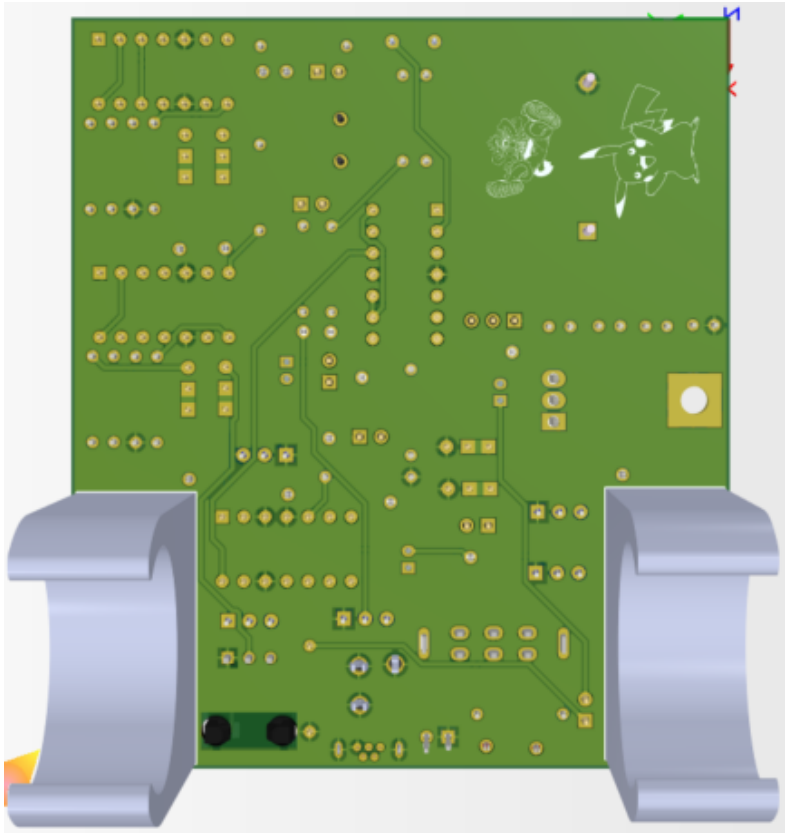


PCB Layout & Design:



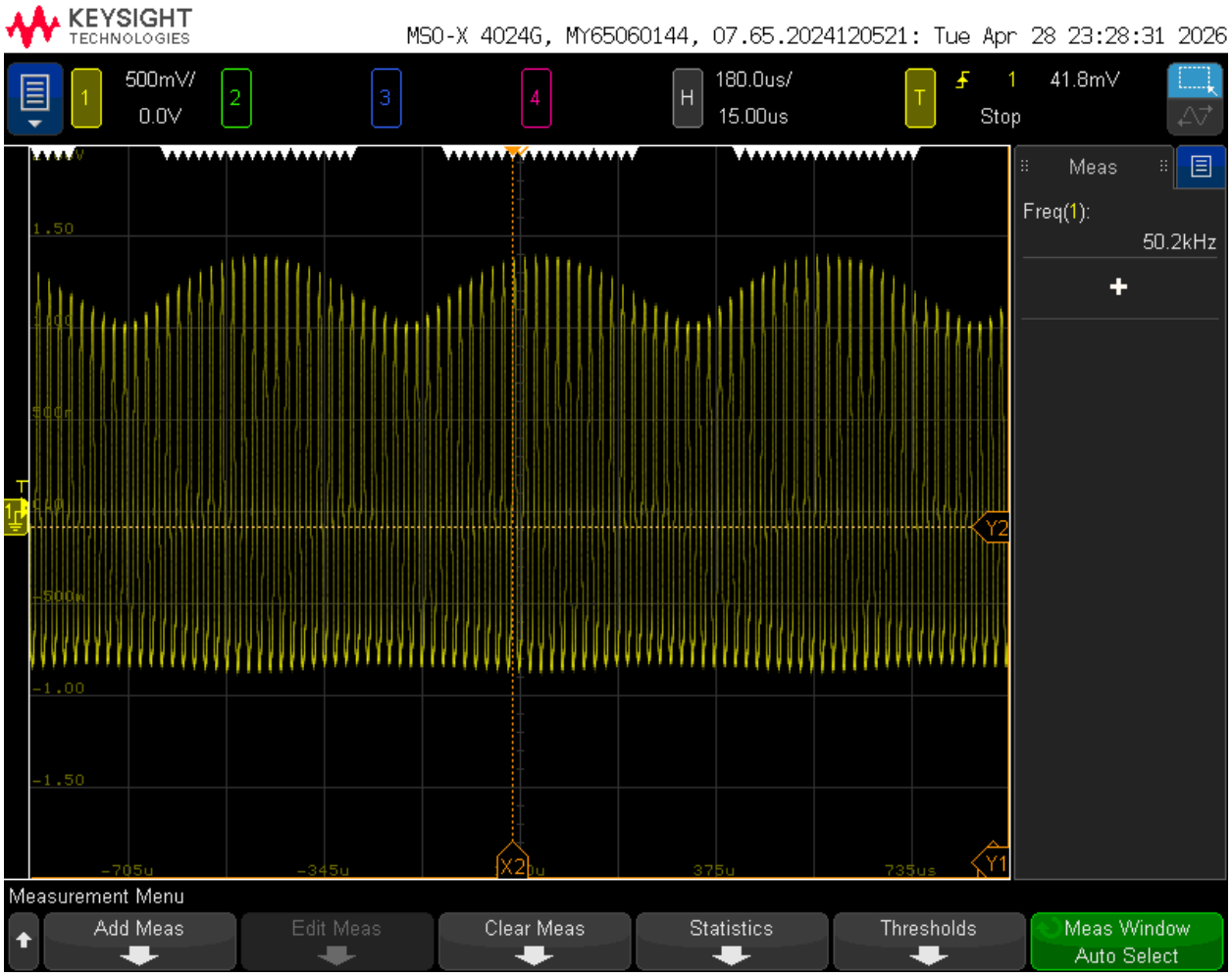



Panos
Dimtsoudis
ESE 319
Spring 26
REMOVE
SEAL
AFTER
WASHING

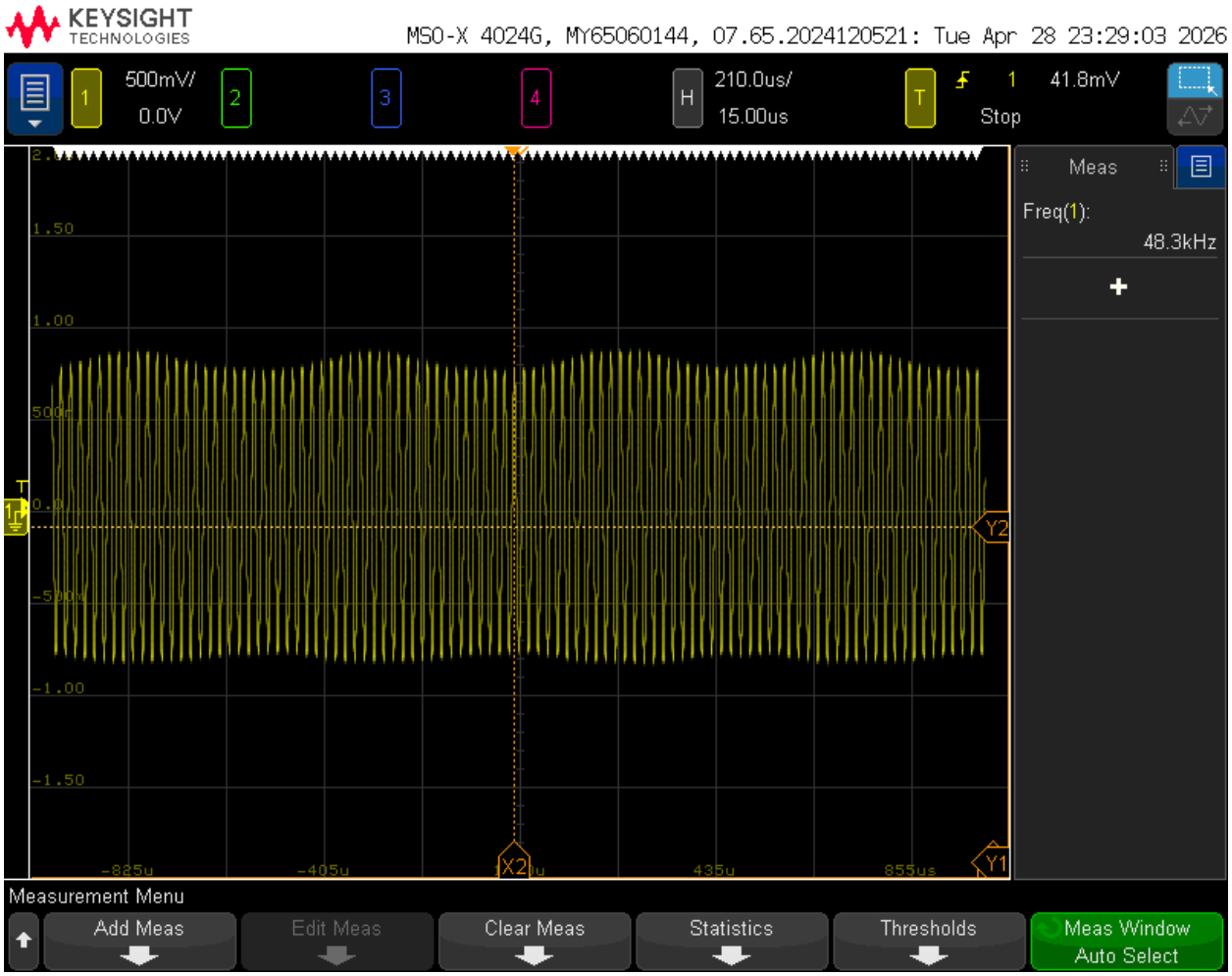


Measurement Results

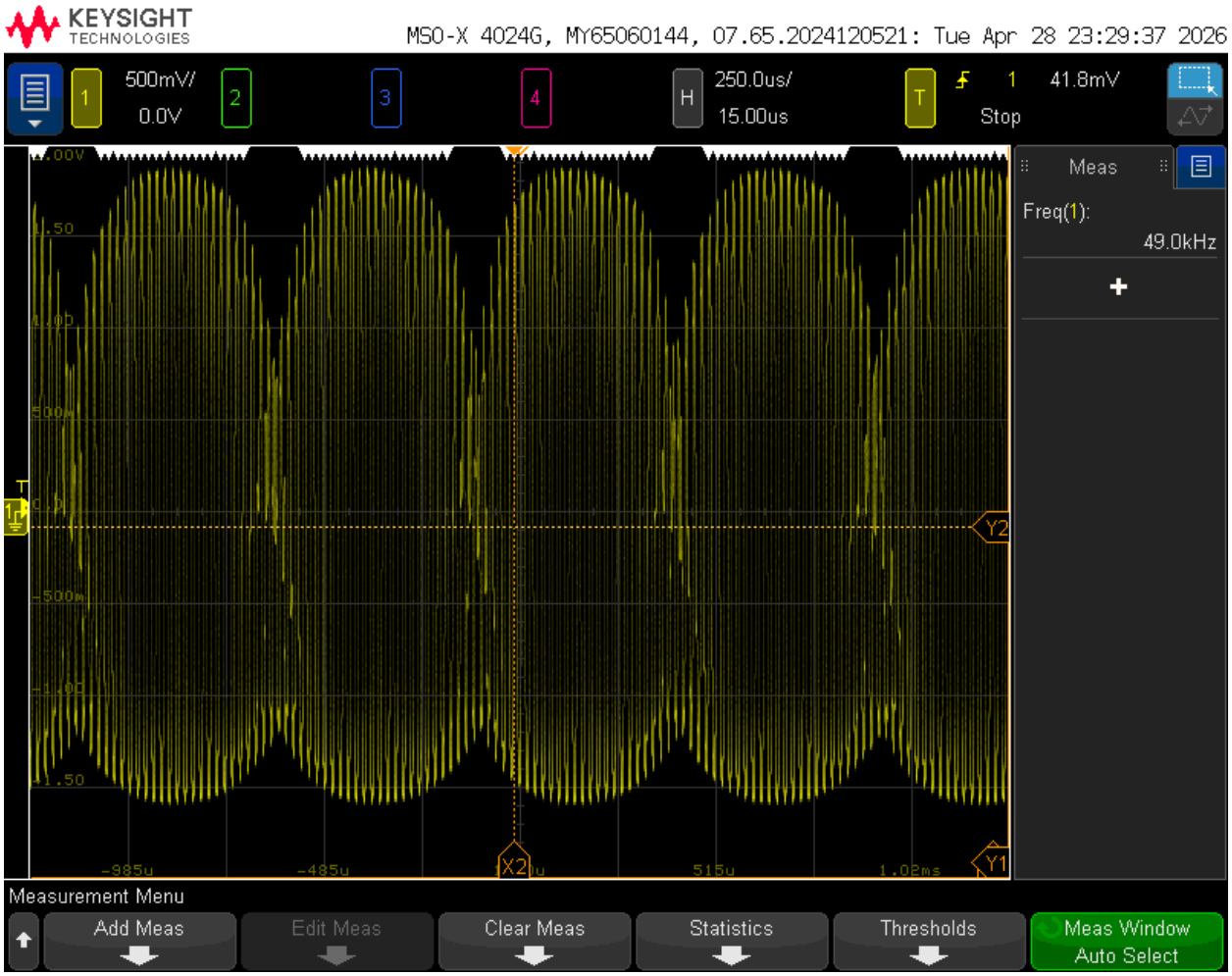
Fixed Oscillator:



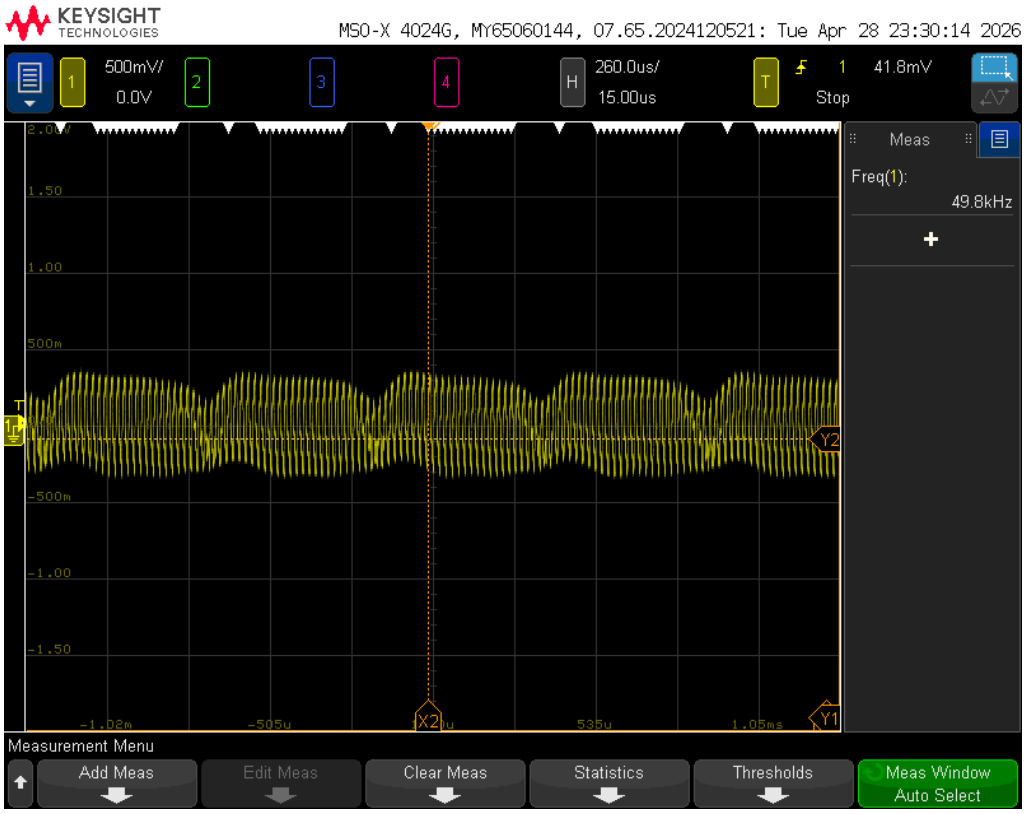
Variable Oscillator:

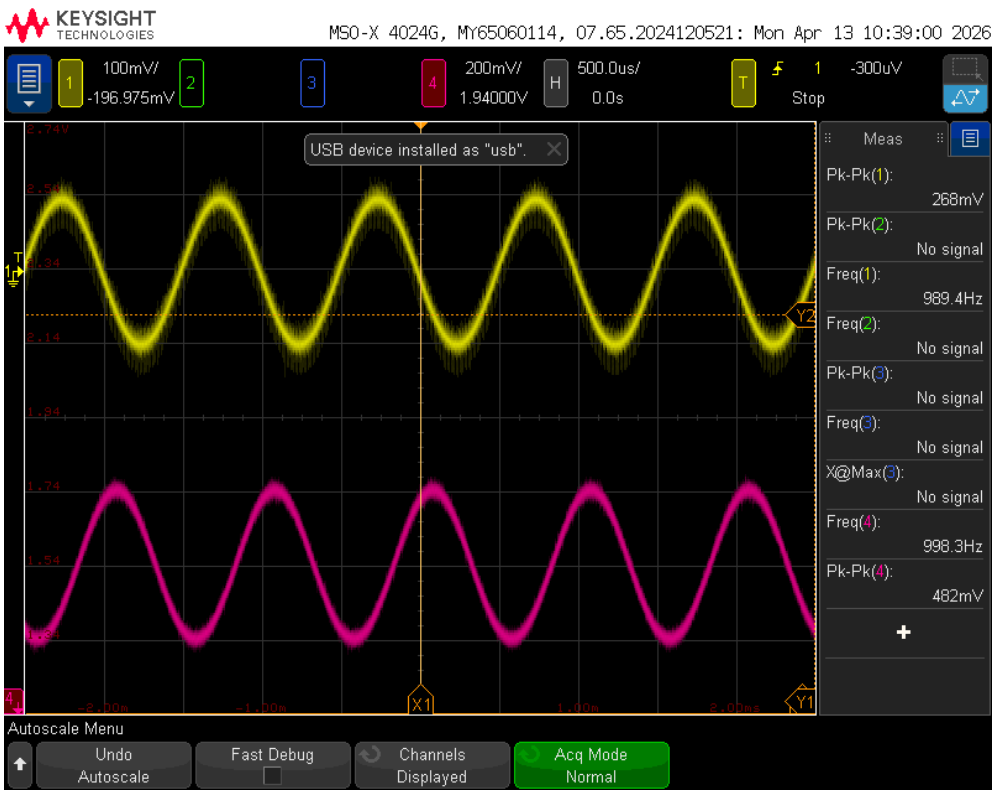


Mixer:

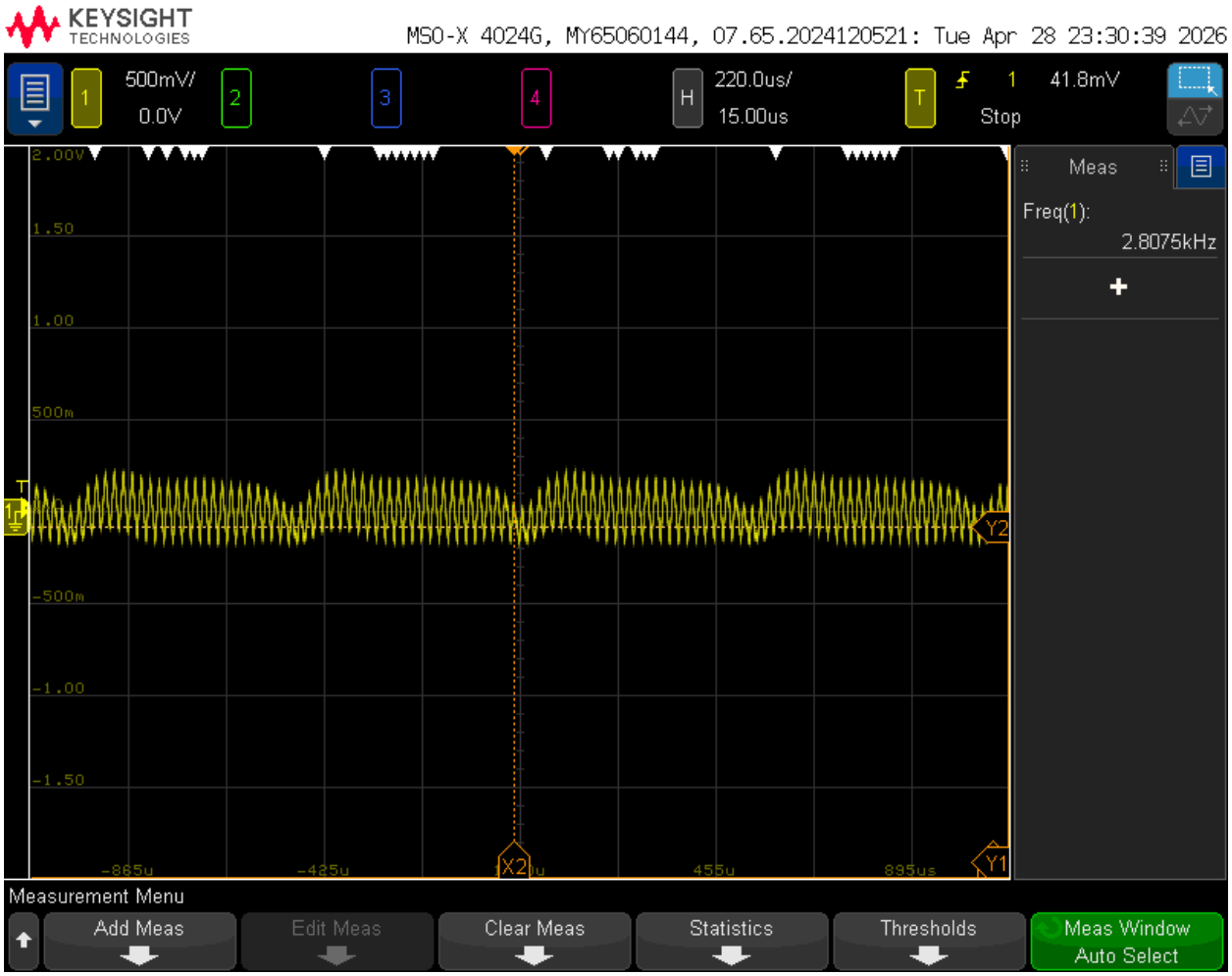

KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060144, 07.65.2024120521: Tue Apr 28 23:29:37 2026
500mV/
0.0V
250.0us/
15.00us
1
41.8mV
Stop
Meas
Freq(1):
49.0kHz
Y2
Y1
X2
-985u
-485u
515u
1.02ms
Measurement Menu
Add Meas
Edit Meas
Clear Meas
Statistics
Thresholds
Meas Window
Auto Select

1st CS:

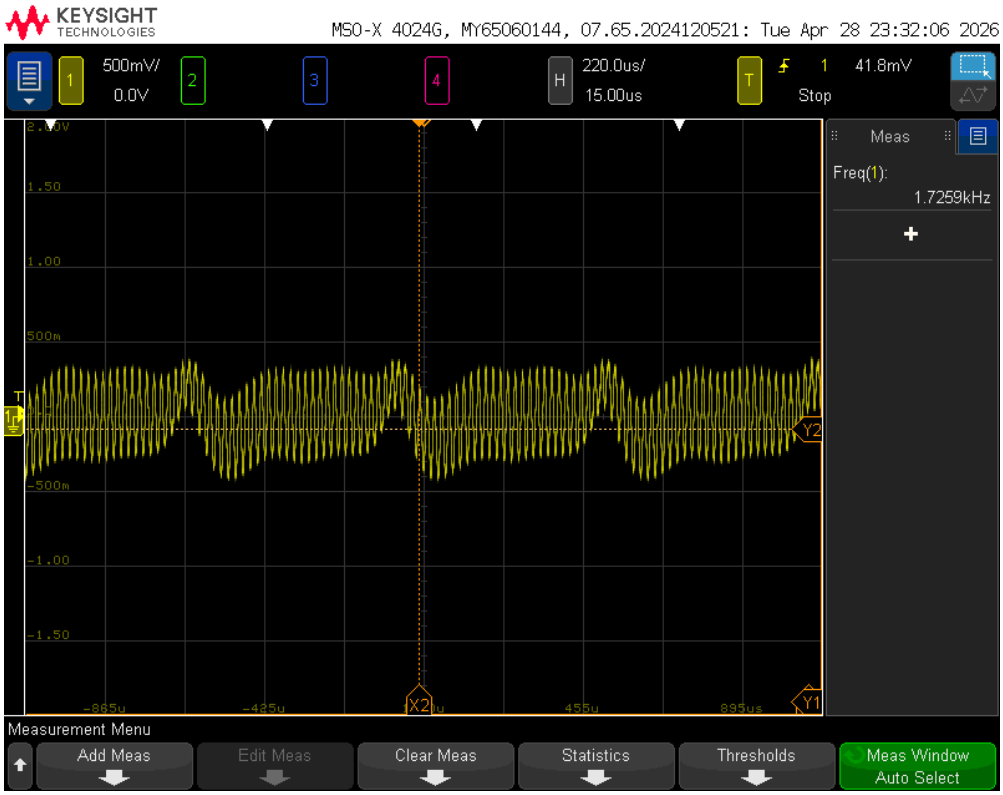

KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060144, 07.65.2024120521: Tue Apr 28 23:30:14 2026
500mV/
0.0V
260.0us/
15.00us
41.8mV
Stop
Meas
Freq(1):
49.8kHz
Measurement Menu
Add Meas
Edit Meas
Clear Meas
Statistics
Thresholds
Meas Window
Auto Select

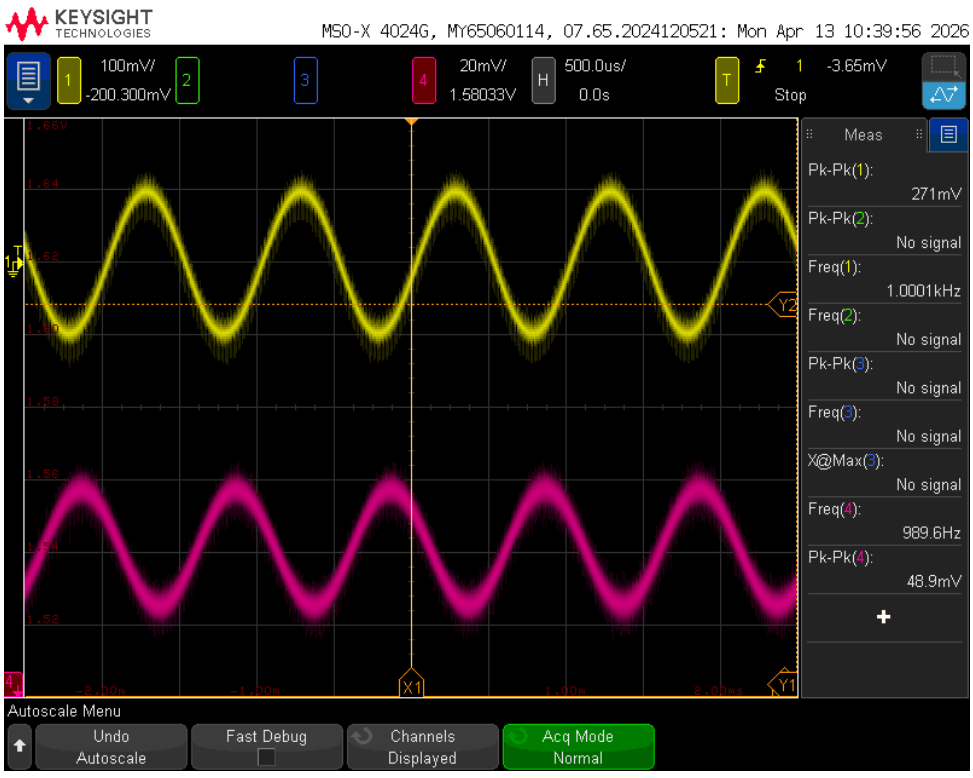

KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060114, 07.65.2024120521: Mon Apr 13 10:39:00 2026
100mV/
-196.975mV
200mV/
1.94000V
500.0us/
0.0s
-300uV
Stop
USB device installed as "usb".
Meas
Pk-Pk(1):
268mV
Pk-Pk(2):
No signal
Freq(1):
989.4Hz
Freq(2):
No signal
Pk-Pk(3):
No signal
Freq(3):
No signal
X@Max(3):
No signal
Freq(4):
998.3Hz
Pk-Pk(4):
482mV
Autoscale Menu
Undo
Autoscale
Fast Debug
Channels
Displayed
Acq Mode
Normal

RC Filter:

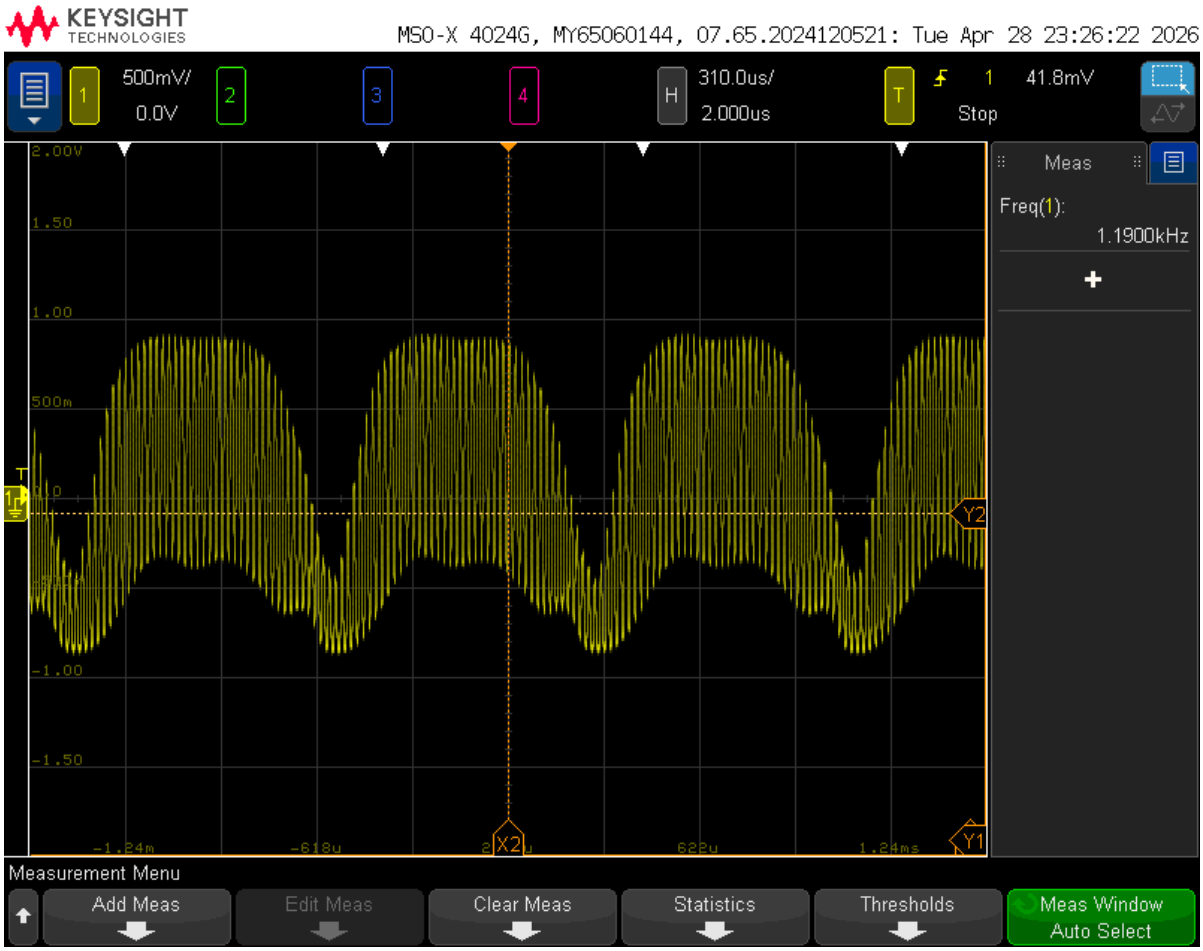

KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060144, 07.65.2024120521: Tue Apr 28 23:30:39 2026
500mV/
0.0V
220.0us/
15.00us
1
41.8mV
Stop
2.00V
1.50
1.00
500m
-500m
-1.00
-1.50
-865u
-425u
455u
895us
Meas
Freq(1):
2.8075kHz
Measurement Menu
Add Meas
Edit Meas
Clear Meas
Statistics
Thresholds
Meas Window
Auto Select

2nd CS:


KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060144, 07.65.2024120521: Tue Apr 28 23:32:06 2026
500mV/
0.0V
220.0us/
15.00us
41.8mV
Stop
Meas
Freq(1):
1.7259kHz
Measurement Menu
Add Meas
Edit Meas
Clear Meas
Statistics
Thresholds
Meas Window
Auto Select


KEYSIGHT TECHNOLOGIES
MSO-X 4024G, MY65060114, 07.65.2024120521: Mon Apr 13 10:39:56 2026
100mV/
-200.300mV
20mV/
1.58033V
500.0us/
0.0s
-3.65mV
Stop
Meas
Pk-Pk(1):
271mV
Pk-Pk(2):
No signal
Freq(1):
1.0001kHz
Freq(2):
No signal
Pk-Pk(3):
No signal
Freq(3):
No signal
X@Max(3):
No signal
Freq(4):
989.6Hz
Pk-Pk(4):
48.9mV
Autoscale Menu
Undo
Autoscale
Fast Debug
Channels
Displayed
Acq Mode
Normal

Output:



Description and Comparison

To test the metal detector, I powered the PCB with a 5 V supply and used the oscilloscope to measure each major stage of the circuit. I probed the fixed oscillator, variable oscillator, mixer, first common-source amplifier, RC filter, second common-source amplifier, and final output stage. For each node, I adjusted the oscilloscope time scale to clearly observe either the high-frequency oscillator signal or the lower-frequency beat signal.

The fixed oscillator measured approximately 50.2 kHz, which was very close to the simulated value of 50.27 kHz. The variable oscillator measured approximately 48.3 kHz, compared to the simulated value of 49.19 kHz. This gives an experimental beat frequency of approximately f = |50.2kHz - 48.3kHz| = 1.9kHz which is in the audible range.

The mixer output showed a high-frequency waveform with a visible amplitude envelope. Although the oscilloscope measured a dominant frequency near 49 kHz, the envelope represented the lower-frequency beat signal created by mixing the two oscillator outputs. After

the first common-source amplifier, the beat signal became stronger, although some high-frequency ripple remained.

The RC filter reduced much of the high-frequency carrier content while allowing the audible beat frequency to pass. The second common-source amplifier then increased the filtered signal level before the final output stage. At the output, the measured waveform had a dominant frequency around 1.19 kHz, confirming that the circuit produced an audible output signal.

Overall, the experimental results matched the expected circuit behavior. The fixed oscillator agreed closely with simulation, while the variable oscillator showed more deviation because it depended on the custom inductor, PCB parasitics, and nearby magnetic effects. The mixer, filter, amplifier stages, and output stage successfully converted the difference between the two oscillator frequencies into an audible signal. The main differences between simulation and measurement were small frequency shifts, waveform distortion, and remaining high-frequency ripple, which are expected in the physical circuit.

Conclusion & Discussion

Overall, the metal detector worked as intended and successfully produced an audible output from the difference between the two oscillator frequencies. The fixed oscillator measured about 50.2 kHz, which closely matched the simulated value of 50.27 kHz. The variable oscillator measured about 48.3 kHz, compared to the simulated value of 49.19 kHz, giving an experimental beat frequency of about 1.9 kHz. Since this frequency is in the audible range, the circuit achieved its main purpose of converting the oscillator frequency difference into a sound-producing signal.

The main mismatch between simulation and experiment came from the variable oscillator. This was expected because the variable oscillator depended on the custom inductor, which is much more sensitive to real-world effects than the fixed inductor. Small differences in winding, coil placement, parasitic capacitance, PCB layout, and nearby metal can all shift the inductance and therefore change the oscillator frequency. In comparison, the fixed oscillator was more stable and matched the simulation more closely.

The mixer produced the expected amplitude-modulated waveform, showing that the two oscillator signals were being combined properly. The RC filter and common-source amplifier stages then helped reduce the high-frequency carrier and strengthen the lower-frequency beat signal. Some high-frequency ripple and distortion remained in the later stages, but this was reasonable because the filter was only first-order and the MOSFET amplifier stages were not perfectly linear in the physical circuit.

Despite these nonidealities, the final output showed an audible-frequency waveform, confirming that the complete system worked. This project demonstrated how LC oscillators, mixing, biasing, filtering, common-source amplification, PCB layout, and oscilloscope measurements all connect in a full analog circuit. If the design were improved further, the main changes would be to tune the variable oscillator more carefully, use a sharper filter to remove more carrier ripple, and adjust the amplifier biasing to reduce distortion.