EE334 µElectronics
Fully Analog Synthesizer
May 17 2024

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Abstract:
For this project, I designed and built a fully analog synthesizer by integrating multiple circuit blocks developed across both the midterm and final phases. Initially, I implemented three core blocks: an audio amplifier, a mixer, and a filter. For the final phase, I expanded the system by constructing and incorporating both low-frequency and high-frequency oscillator circuits. Once all five modules were built and tested, I combined them into a single cohesive circuit. Key design decisions included using a single NMOS transistor for amplification in place of traditional NPN BJTs, implementing a fourth-order Sallen-Key configuration for the filter block, and using a simple diode-based mixer. For oscillation, I employed a 555 timer IC to generate the low-frequency square wave and a Wien bridge oscillator for the high-frequency output. I evaluated the final system against LTSpice simulations and theoretical models to ensure each stage performed as expected, resulting in a fully functional analog synthesizer.

Introduction:
In order to complete the synthesizer, I needed to analyze, simulate, and build this large circuit one block at a time. For the first half of the circuit, I focused on ensuring that the mixer, filter, and amplifier were functioning well together. Much like the first phase of the project, I then worked to complete the remaining blocks of the synthesizer diagram, as shown in Fig. 0 of the midterm report. These remaining blocks included the oscillators and the output stage. This phase centered primarily on designing those new sections, while still relying on the earlier blocks for testing and output measurements.

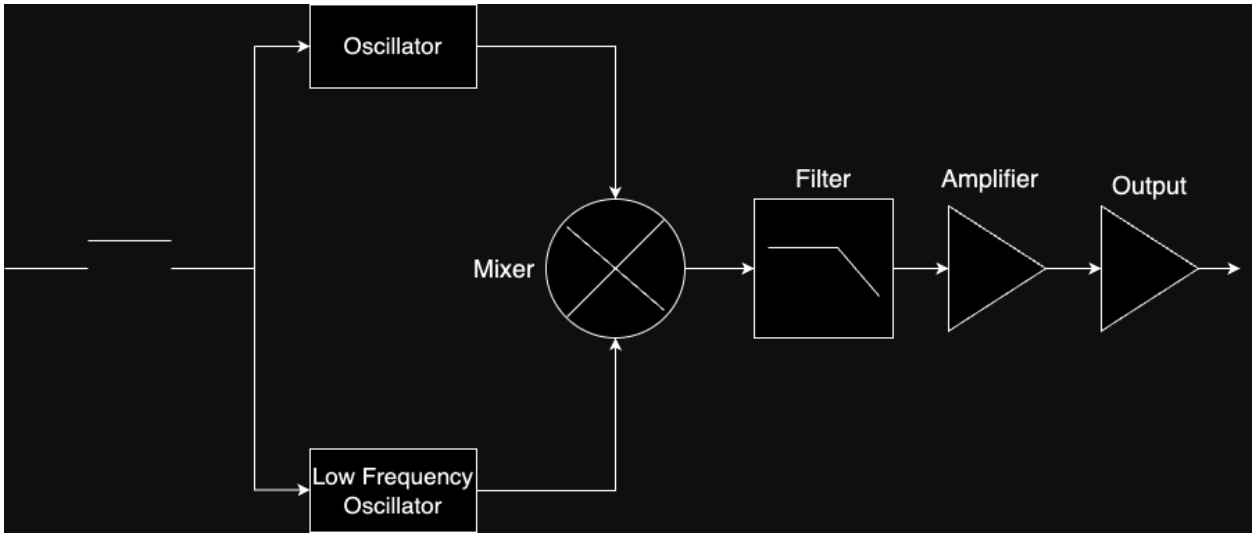

Fig.0 Block Diagram of Full Synthesizer

Table 1: List of Materials

Component	Schematic name	Value	Measured Value	Percent Error
LM741	U1	-	-	-
LM741	U2	-	-	-
Diode (1N4148)	D1	-	-	-
TP3904	Q1	-	-	-
TP3904	Q2	-	-	-
Resistor	R18	1.5 kΩ	1.503 kΩ	0.2%
Resistor	R19	1 kΩ	0.998 kΩ	0.2%
Resistor	R4	0.500 kΩ	0.508 kΩ	0.39%
Resistor	R5	0.150 kΩ	0.1498 kΩ	0.13%
Resistor	R15	15 kΩ	14.99 kΩ	0.07%
Resistor	R8	0.500 kΩ	0.504 kΩ	1.17%
Resistor	R9	0.150 kΩ	0.1496 kΩ	0.26%
Resistor	R11	22.00 kΩ	22.10 kΩ	0.4%
Resistor (LOAD - not utilized in demo but present on schematic)	RL	15 Ω	14.99 Ω	0.07%
Resistor	R21	1 kΩ	0.996 kΩ	0.4%
Resistor	R1	10k kΩ	9.96 kΩ	0.4%
Resistor	R14	5. kΩ	5.09 kΩ	0.19%
Resistor	R12	10 kΩ	10 kΩ	0%
Resistor	R13	10 kΩ	10 kΩ	0%
Resistor	R16	47.0 kΩ	47.2 kΩ	0.43%
Resistor	R3	100.0 kΩ	100.5 kΩ	0.5%

Resistor	R10	10 kΩ	10 kΩ	0%
Resistor	R7	22.00 kΩ	22.11 kΩ	0.5%
Resistor	R2	10.0 kΩ	9.97 kΩ	0.29%
Resistor	R6	10 kΩ	9.97 kΩ	0.3%
Resistor	R17	100 kΩ	99.4 kΩ	0.59%
Capacitor	C1	47 µF	49 µF	4.25%
Capacitor	C4	0.1 µF	0.103 uF	3%
Capacitor	C2	47 µF	51 µF	8.51%
Capacitor	C6	0.1 µF	0.109 µF	9%
Capacitor	C7	47 µF	44.5 µF	5.31%
Capacitor	C8	47 µF	52 µF	10.64%
Capacitor	C9	47 µF	44.85 µF	4.57%
Capacitor	C10	47 µF	49 µF	4.5%
Capacitor	C3	75 nF	64 µF	15%
Capacitor	C5	75 nF	82 µF	9%

Component	Schematic name	Value	Measured Value	Percent Error
LM741	U1	-	-	-
LM741	U2	-	-	-
Diode (1N4148)	D1	-	-	-
TP3904	Q1	-	-	-
TP3904	Q2	-	-	-
Resistor	R18	1.5 kΩ	1.503 kΩ	0.2%
Resistor	R19	1 kΩ	0.998 kΩ	0.2%
Resistor	R4	0.500 kΩ	0.508 kΩ	0.39%

Resistor	R5	0.150 kΩ	0.1498 kΩ	0.13%
Resistor	R15	15 kΩ	14.99 kΩ	0.07%
Resistor	R8	0.500 kΩ	0.504 kΩ	1.17%
Resistor	R9	0.150 kΩ	0.1496 kΩ	0.26%
Resistor	R11	22.00 kΩ	22.10 kΩ	0.4%
Resistor	RL	100 Ω	100.8 Ω	0.07%
Resistor	R21	1 kΩ	0.996 kΩ	0.4%
Resistor	R1	10k kΩ	9.96 kΩ	0.4%
Resistor	R14	5. kΩ	5.09 kΩ	0.19%
Resistor	R12	10 kΩ	10 kΩ	0%
Resistor	R13	10 kΩ	10 kΩ	0%
Resistor	R16	47.0 kΩ	47.2 kΩ	0.43%
Resistor	R3	100.0 kΩ	100.5 kΩ	0.5%
Resistor	R10	10 kΩ	10 kΩ	0%
Resistor	R7	22.00 kΩ	22.11 kΩ	0.5%
Resistor	R2	10.0 kΩ	9.97 kΩ	0.29%
Resistor	R6	10 kΩ	9.97 kΩ	0.3%
Resistor	R17	100 kΩ	99.4 kΩ	0.59%
Potentiometer	R23	10 k	-	-
Potentiometer	R33	10 k	-	-
Potentiometer	R44	300 k	-	-
Potentiometer	R24	10 k	-	-
Potentiometer	R25	10 k	-	-
Capacitor	C1	47 µF	49 µF	4.25%
Capacitor	C4	0.1 µF	0.103 uF	3%
Capacitor	C2	47 µF	51 µF	8.51%

Capacitor	C6	0.1 µF	0.109 µF	9%
Capacitor	C7	47 µF	44.5 µF	5.31%
Capacitor	C8	47 µF	52 µF	10.64%
Capacitor	C9	47 µF	44.85 µF	4.57%
Capacitor	C10	47 µF	49 µF	4.5%
Capacitor	C3	75 nF	64 µF	15%
Capacitor	C5	75 nF	82 µF	9%
LM741	U1	-	-	-
LM741	U2	-	-	-
Diode (1N4148)	D1	-	-	-
TP3904	Q1	-	-	-

Mixer Block:

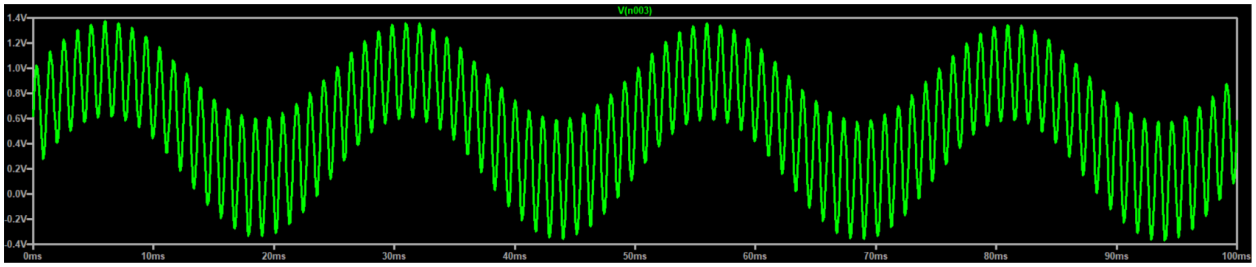

Fig.1 Mixer Simulation

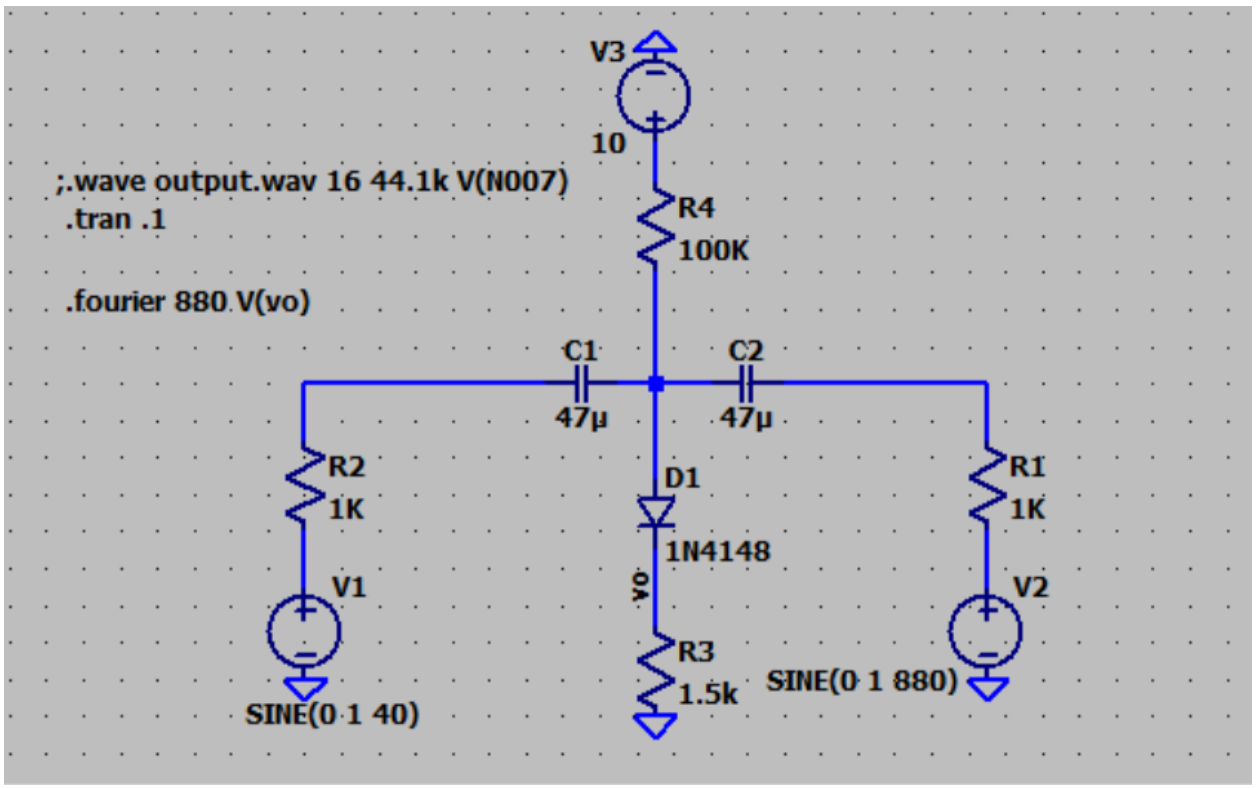

Fig.2 Mixer Schematic

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Partial Harmonic Distortion: 28.634069%
Total Harmonic Distortion:   28.798702%
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Fig.3 Mixer Harmonic Results

The figures above show the mixer portion of our circuit in LTSpice. Our goal when designing the mixer was to achieve the highest possible harmonic distortion to gain the

most pleasant sounding output possible which is shown as total and partial harmonic distortion.

Filter Block:

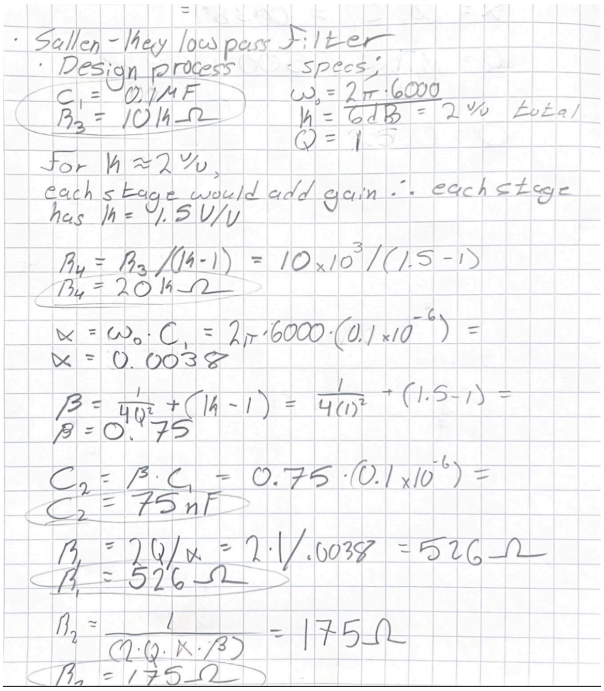

Fig.4 Filter Hand Calculations 1

The figure above shows calculations for ideal components.

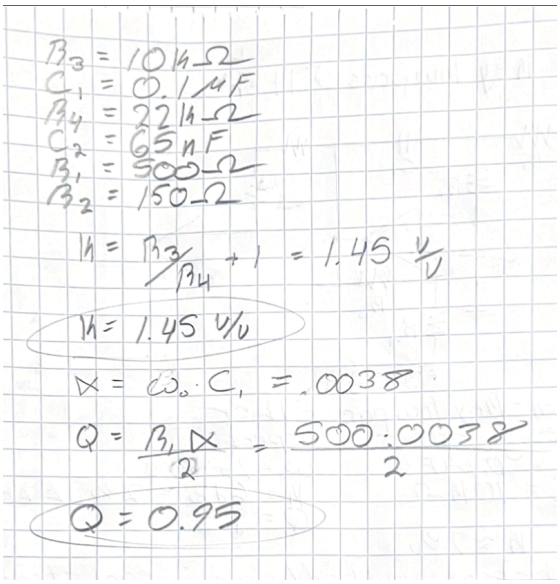

Fig.5 Filter Hand Calculations 2

The figure above shows specifications for the values that were implemented into the circuit.

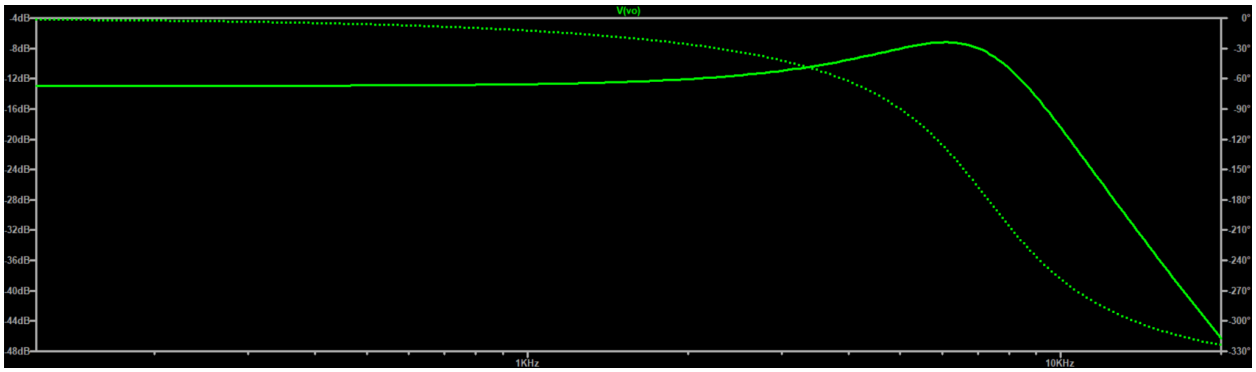

Fig.6 Filter Frequency Response

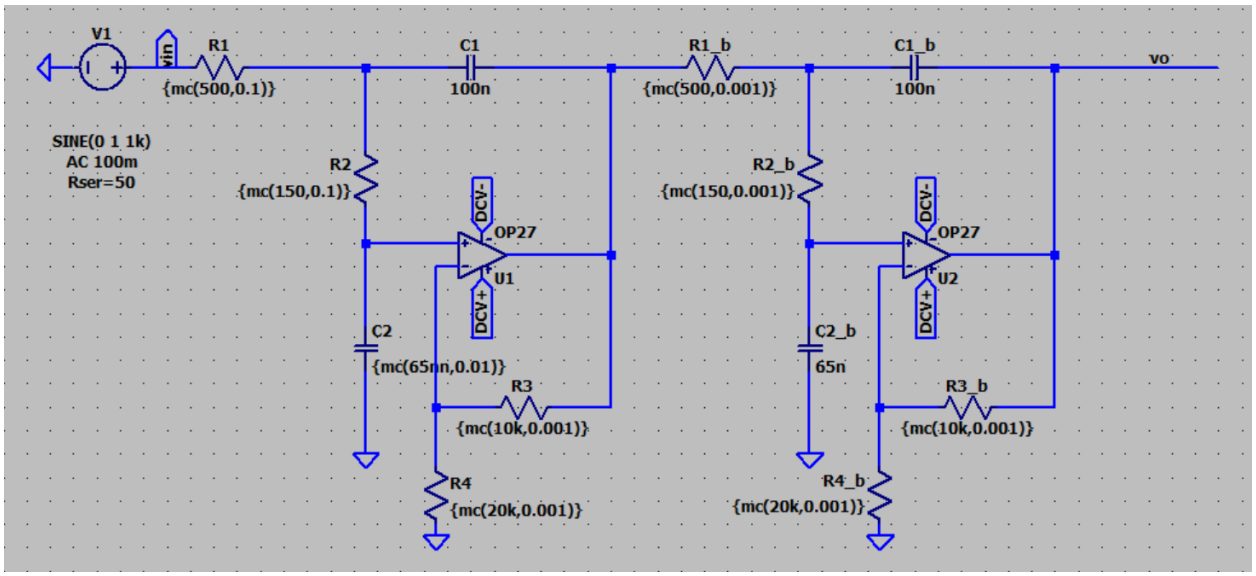

Fig.7 Filter Schematic

The figures above show the frequency response and circuit schematic of the 4th order filter circuit in LTSpice.

Amplifier Block:

$$A_v = -g_m R_D$$

$$A_v = 20\ V/V\ \&\ R_D = 5.1\ k\Omega$$

$$\Rightarrow g_m = \frac{20}{5.1}\ mA/V$$

$$g_m = 3.91\ mA/V$$

$$g_m = k_n(V_{GS} - V_{tn}) = k_n V_{ov}$$

$$\mathrm{k_n} = 0.17\ \mathrm{V^2/mA}$$

$$\Rightarrow V_{ov} = \frac{g_m}{k_n}$$

$$V_{ov} = \frac{0.0039}{0.17}$$

$$V_{ov} = 0.023$$

$$V_{GS} = V_{ov} + V_{tn}$$

$$V_{tn} = 2.45\ V$$

$$V_{GS} = 2.47\ \mathrm{V}$$

$$I_\mathrm{D} = \frac{1}{2} k_n V^2_{ov}$$

$$I_\mathrm{D} = 45\ uA$$

$$R_\mathrm{S} = \frac{V_{GS}}{I_D}$$

$$R_\mathrm{S} \approx 54\ k\Omega$$

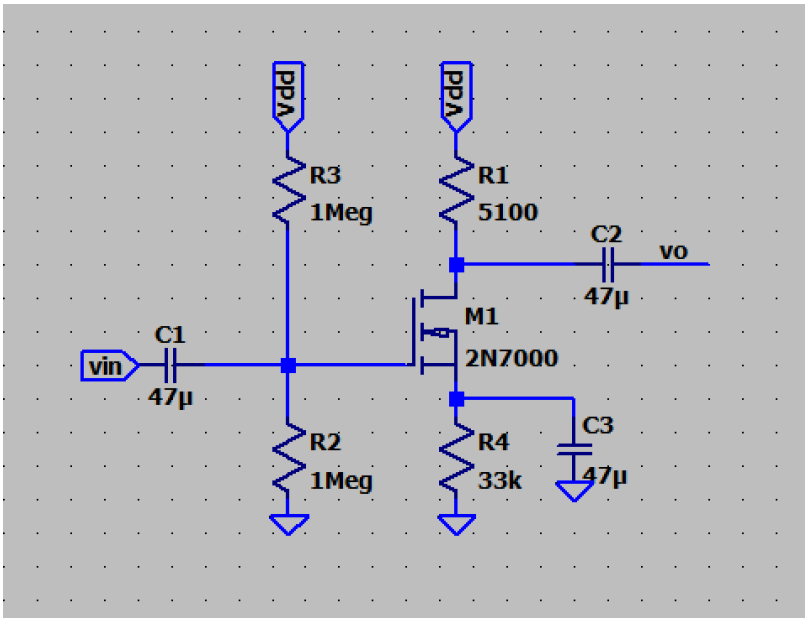

Fig.8 Amplifier Schematic

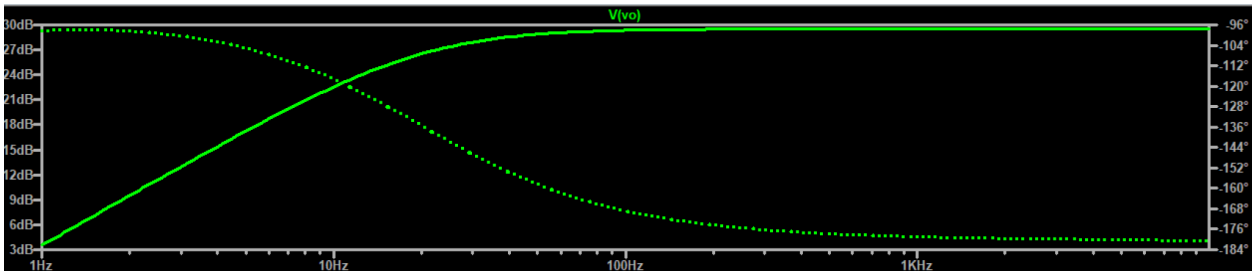

Fig.9 Amplifier Frequency Response

The figures above show our simulated circuit in LTSpice and a simulated frequency response. The components used came from our utilization of the given design tips, and the components we had access to.

Low Frequency Oscillator:

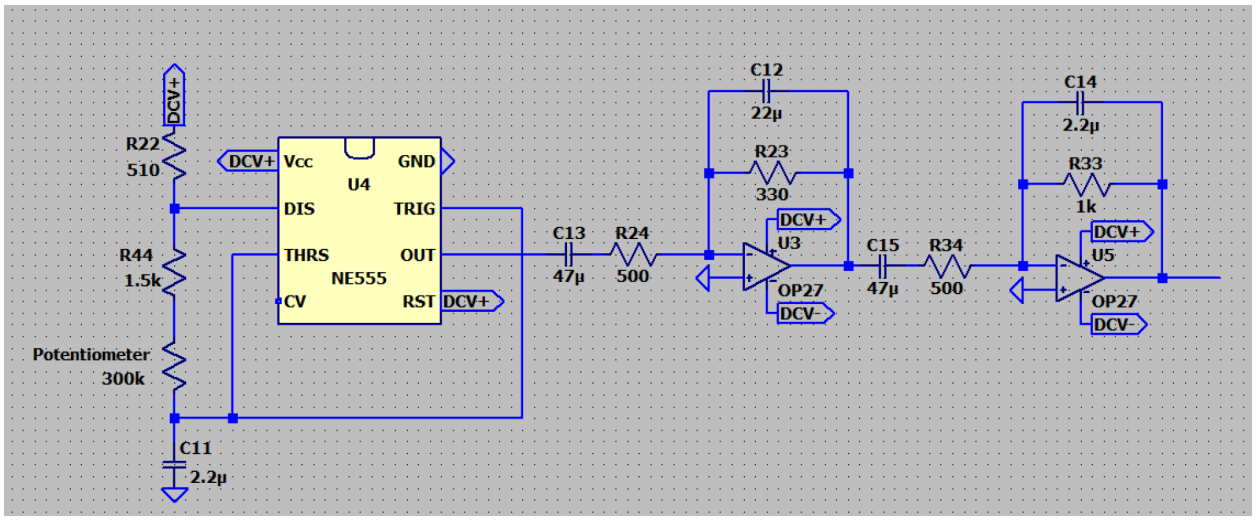

Fig.10 LFO Schematic

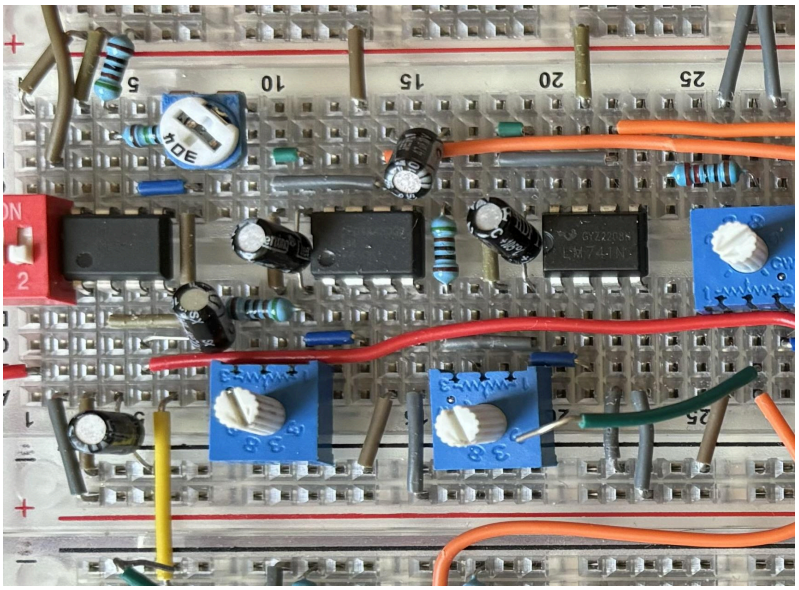

Fig.37 Real Circuit

High Frequency Oscillator:

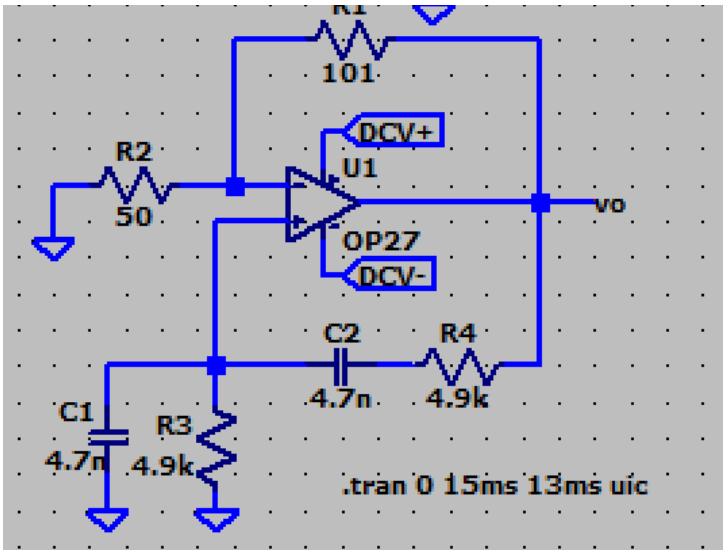

Fig.11 HFO Schematic

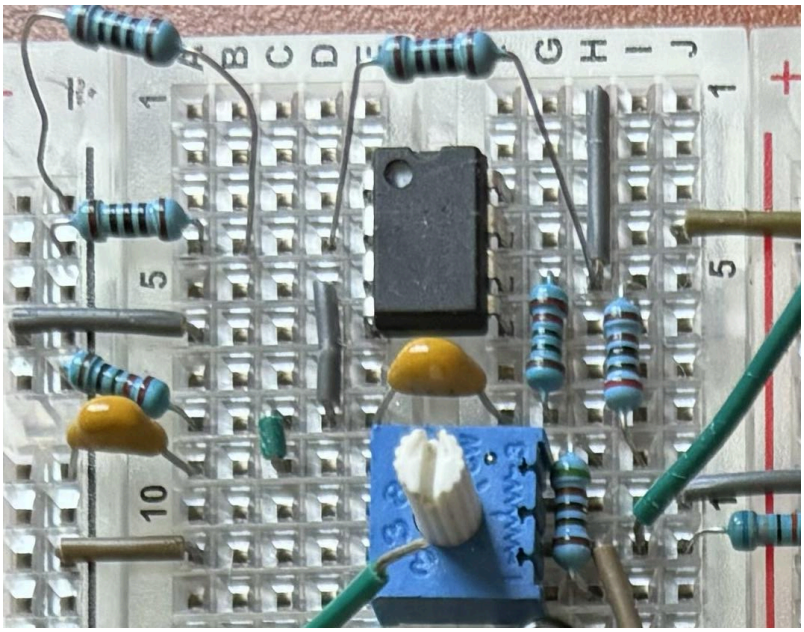

Fig.12 Real Circuit

Output Stage:

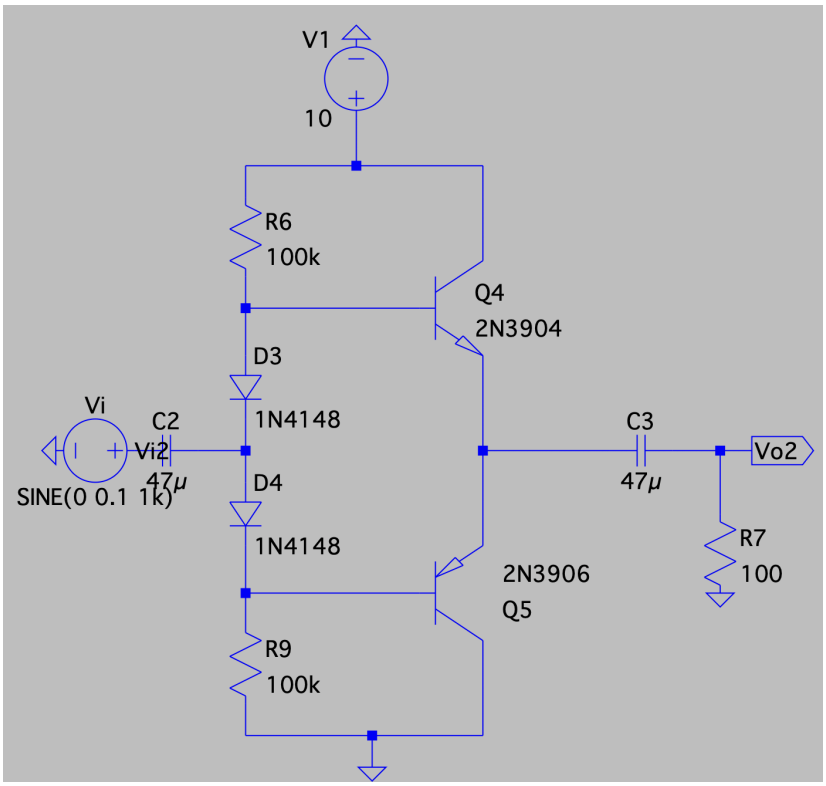

Fig.13 Class AB Schematic

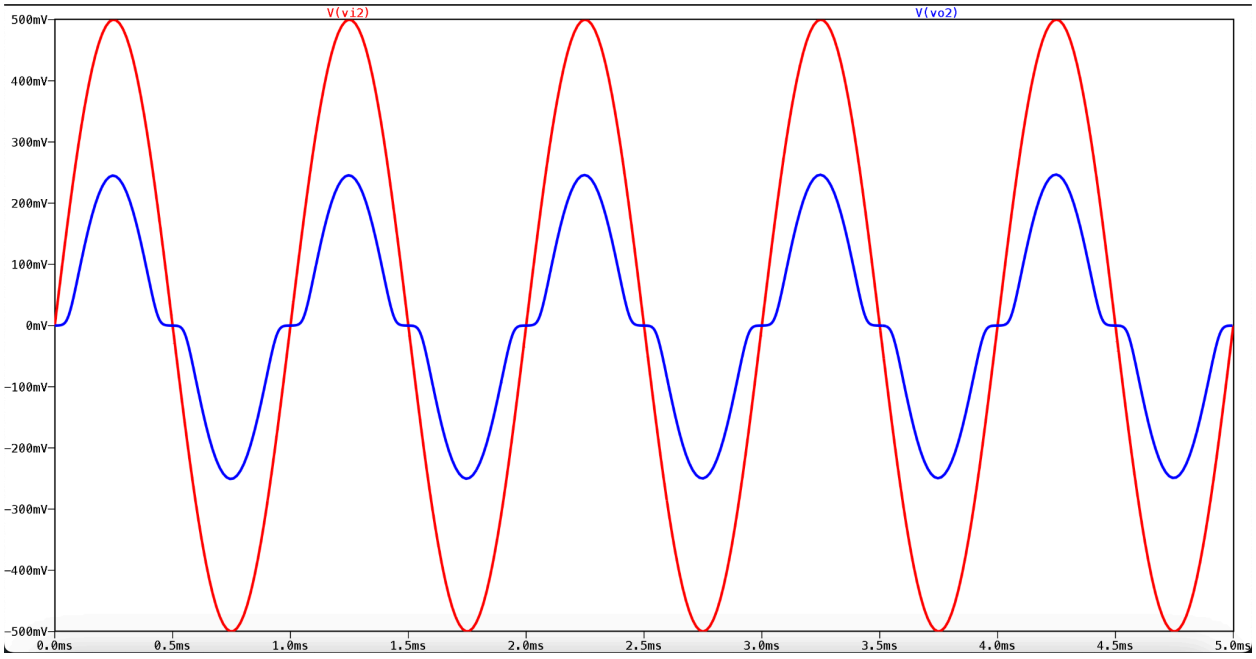

Fig.14 LTspice Plot for Output Stage

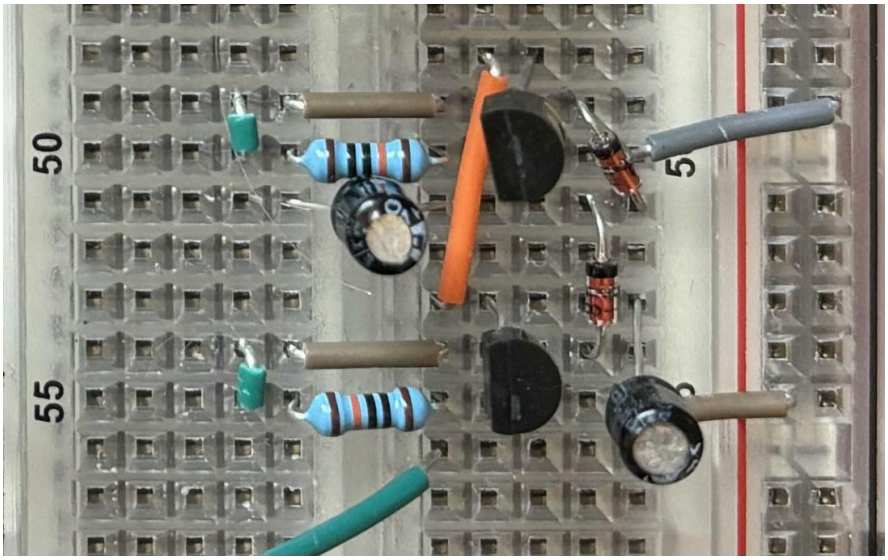

Fig.15 Real Circuit

Noise Generator:

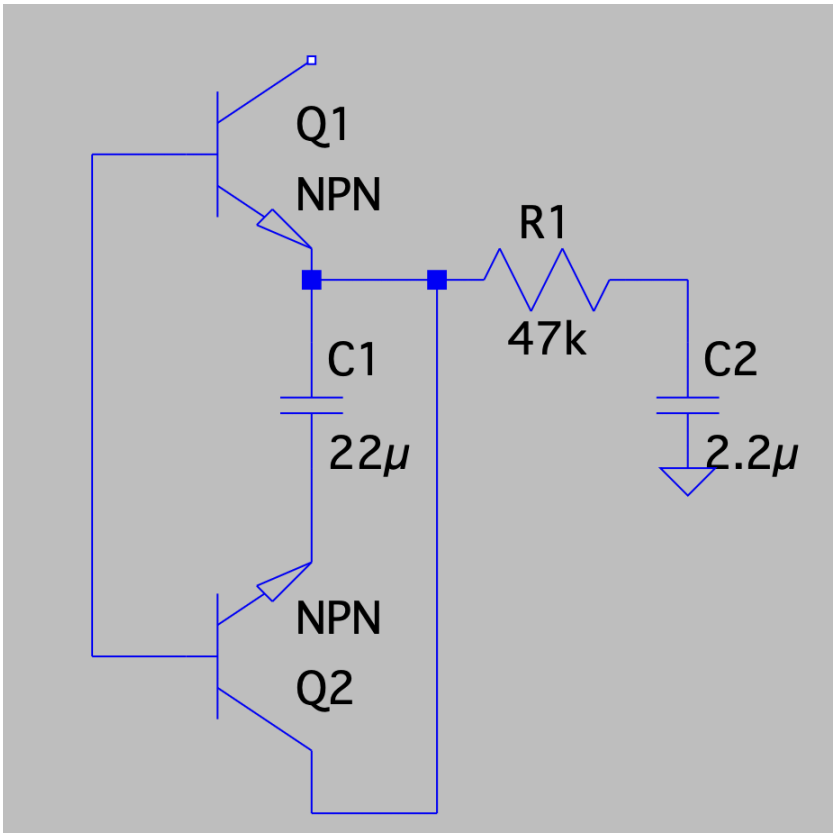

Fig.16 Noise Gen. Schematic

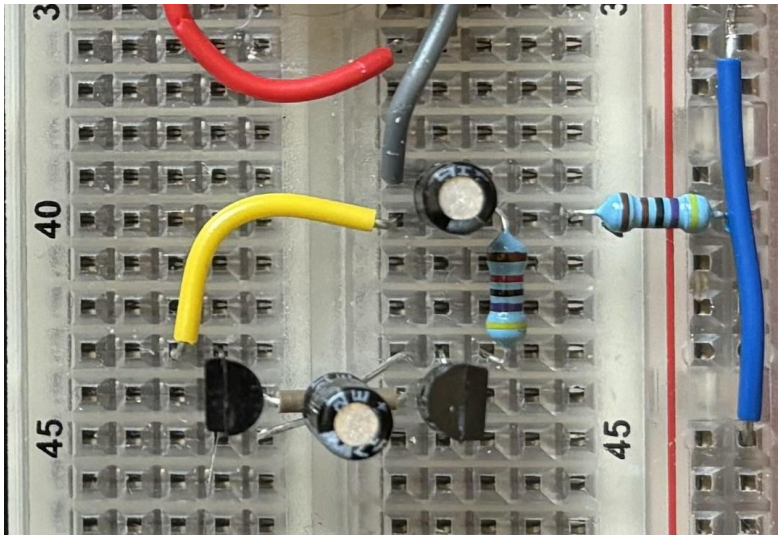

Fig.17 Real Circuit

Midterm Demonstration screenshots:

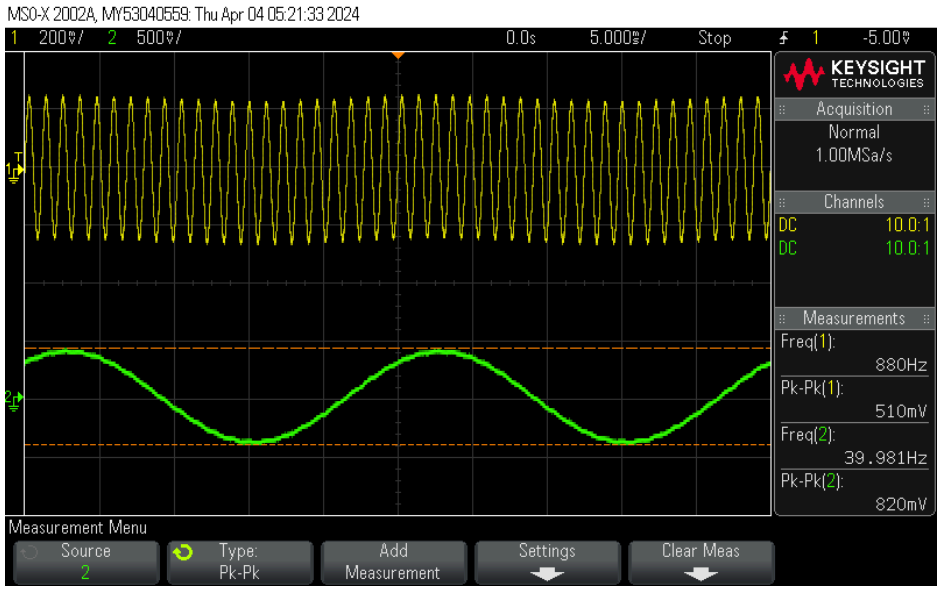

Fig.18, first set of input signals

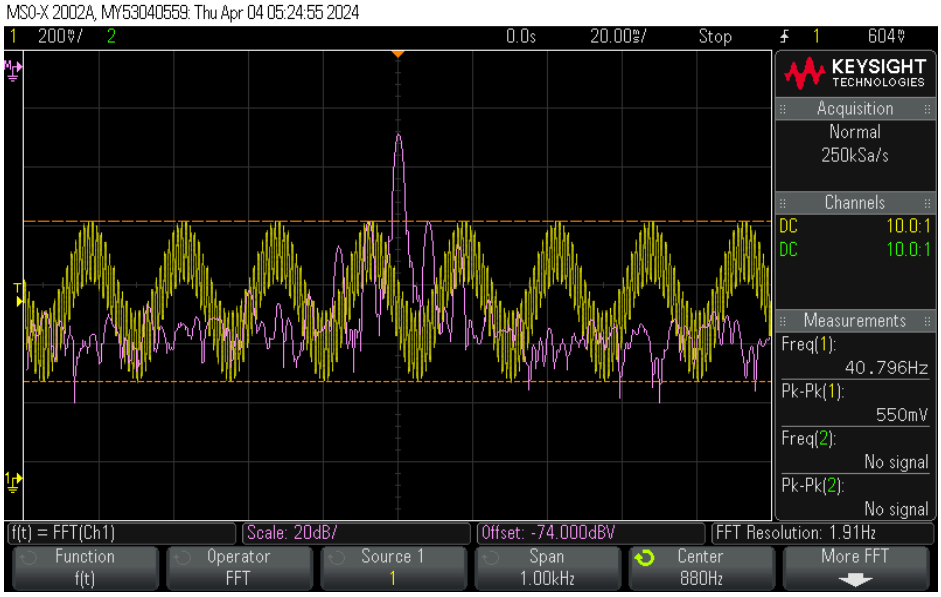

Fig.19, output of mixer stage

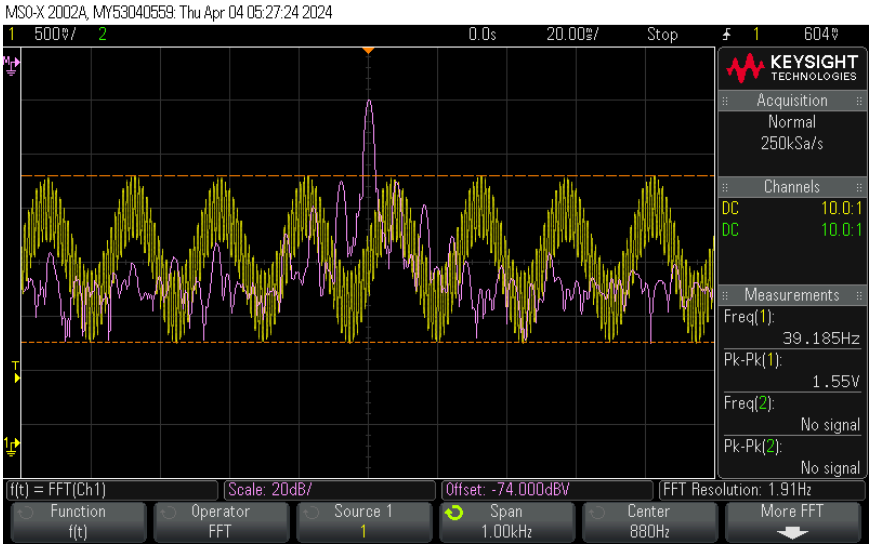

Fig.20, output of filter stage

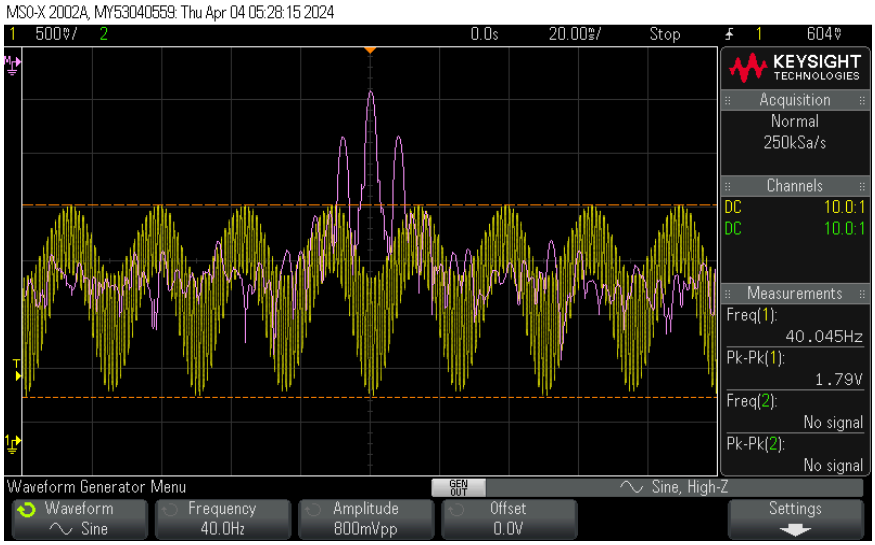

Fig.21, output of amplifier stage

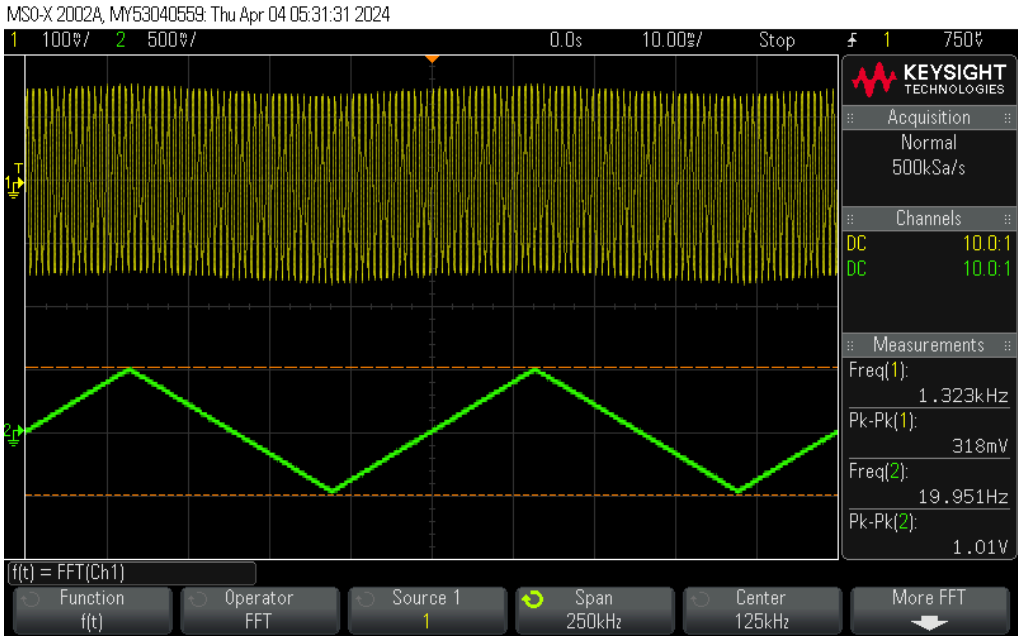

Fig.22, second set of input signals

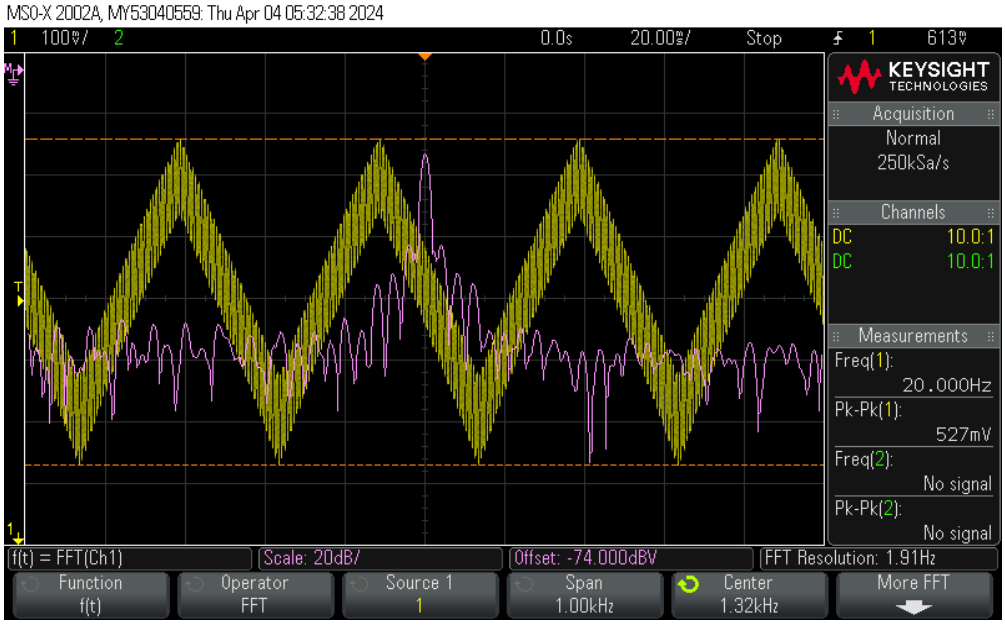

Fig.23, Output of Mixer Stage (Second Set)

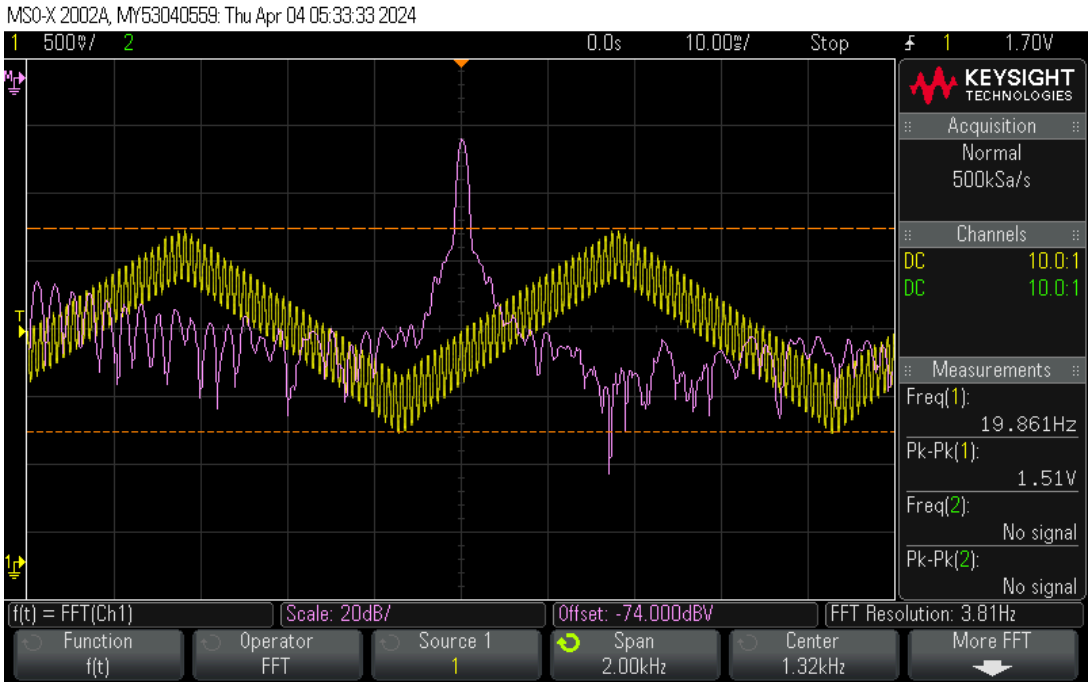

Fig.24, Output of Filter Stage (Second Set)

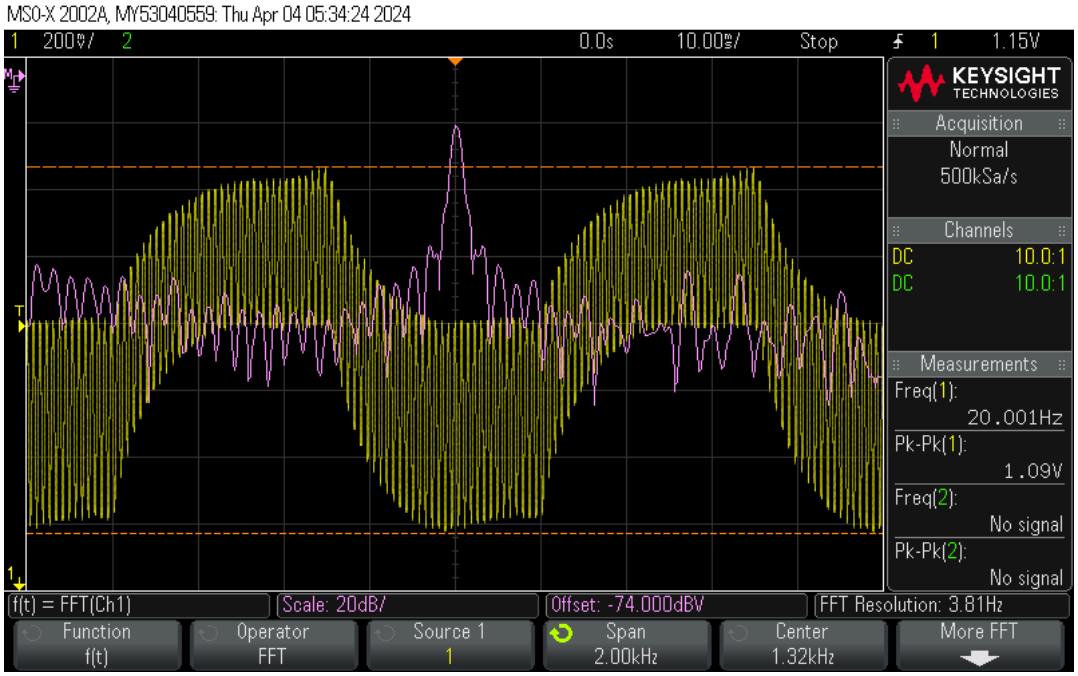

Fig.25, Output of Amplifier Stage (Second Set)

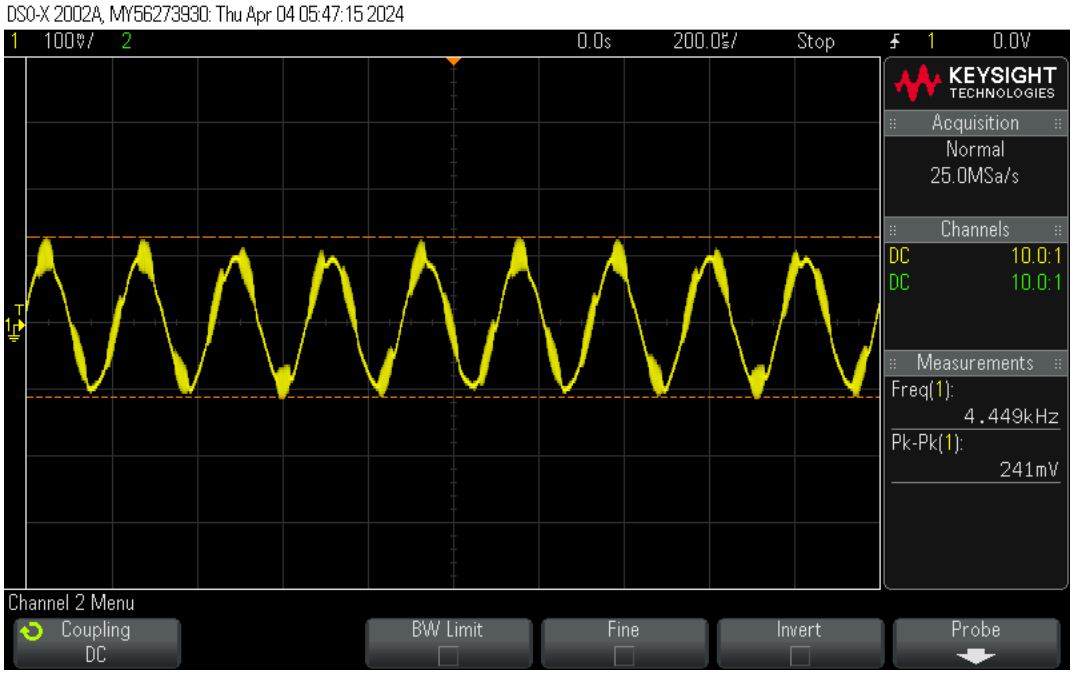

Fig.26_1, 4.5 kHz Sine-wave Input (Third set)

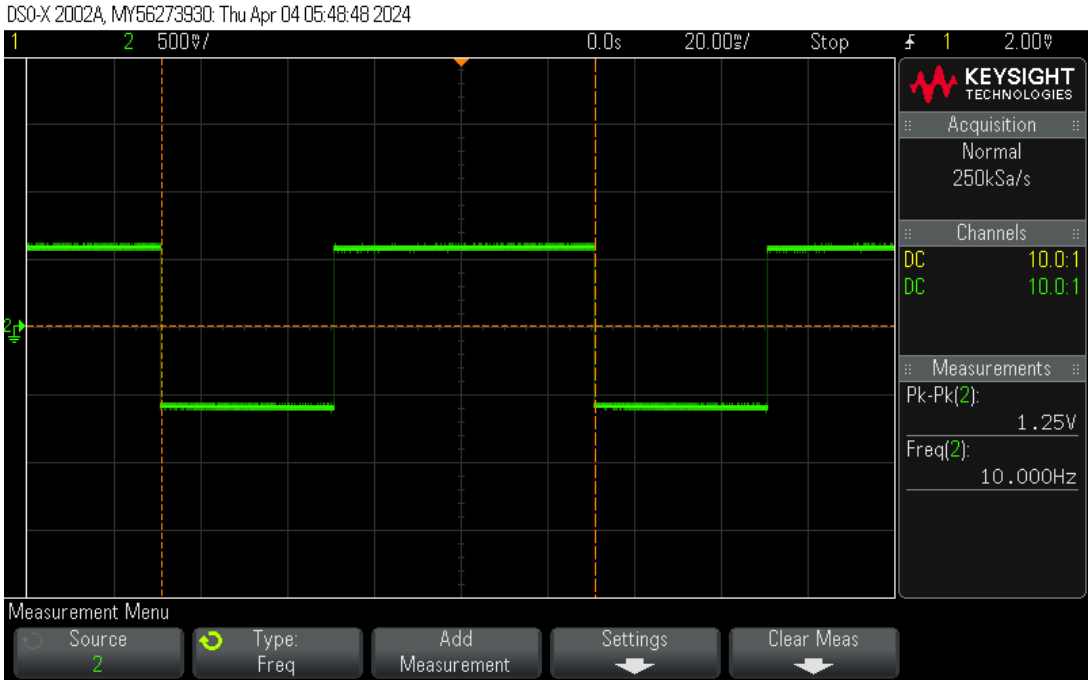

Fig.26_2, 10 Hz Square-wave Input (Third set)

Fig.27, Output of Mixer Stage (Third Set)

Fig.28, Output of Filter Stage (Third Set)

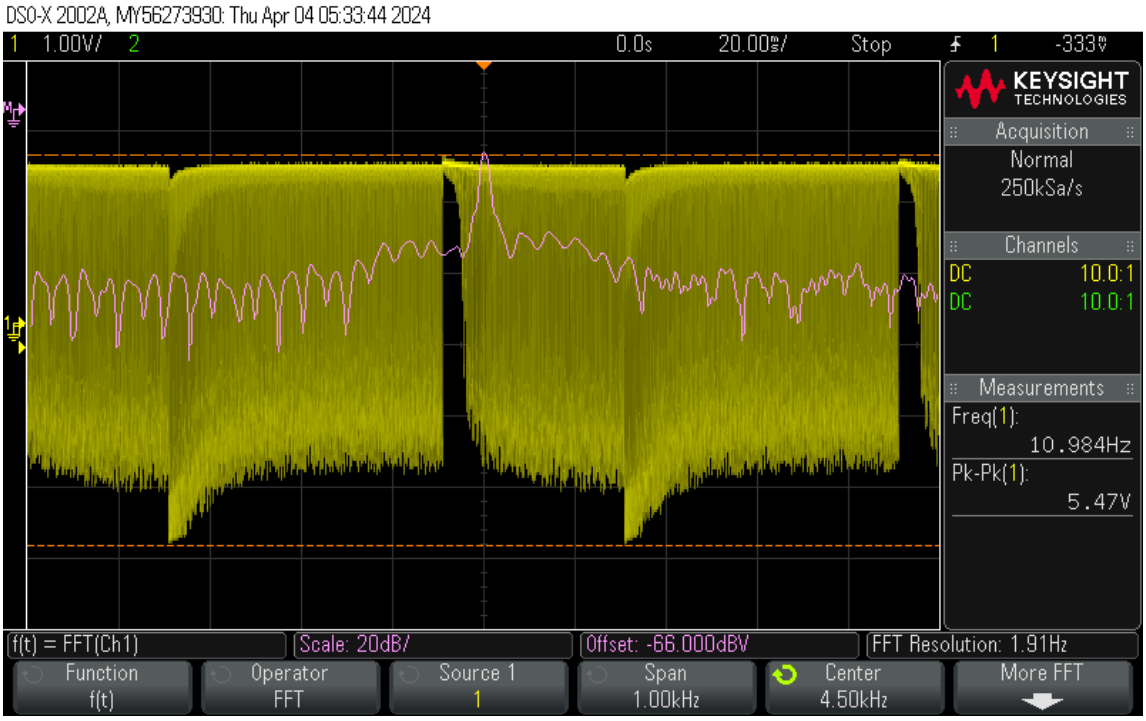

Fig.29, Output of Amplifier Stage (Third Set)

Final Demonstration Screenshots:

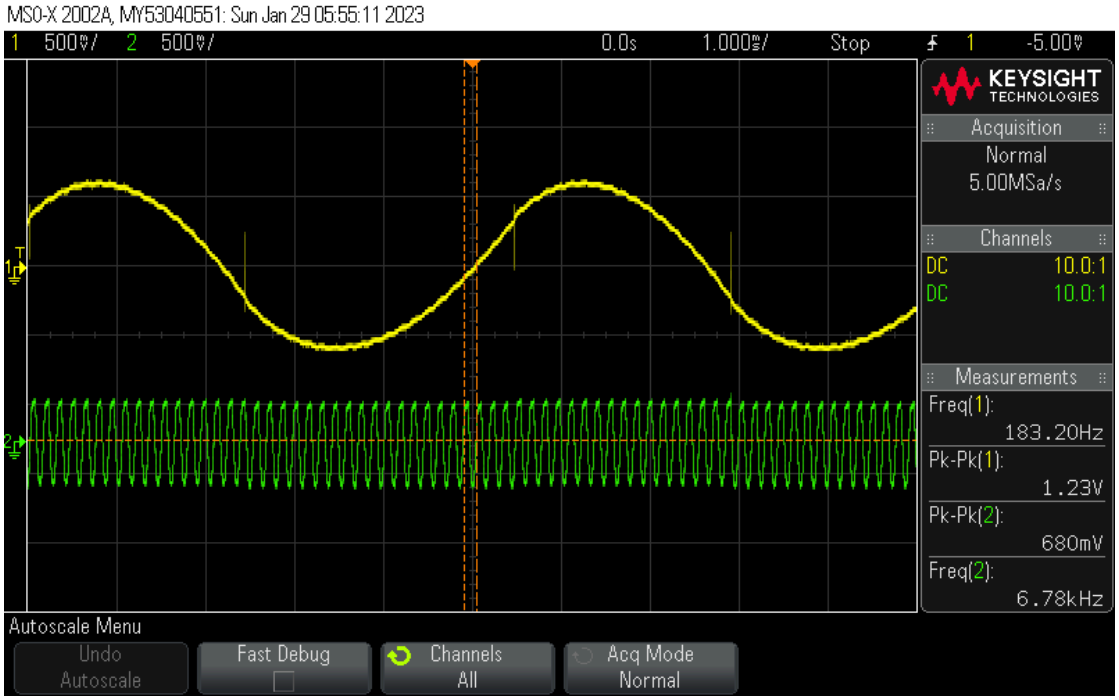

Fig.30 First Set Input Waveforms

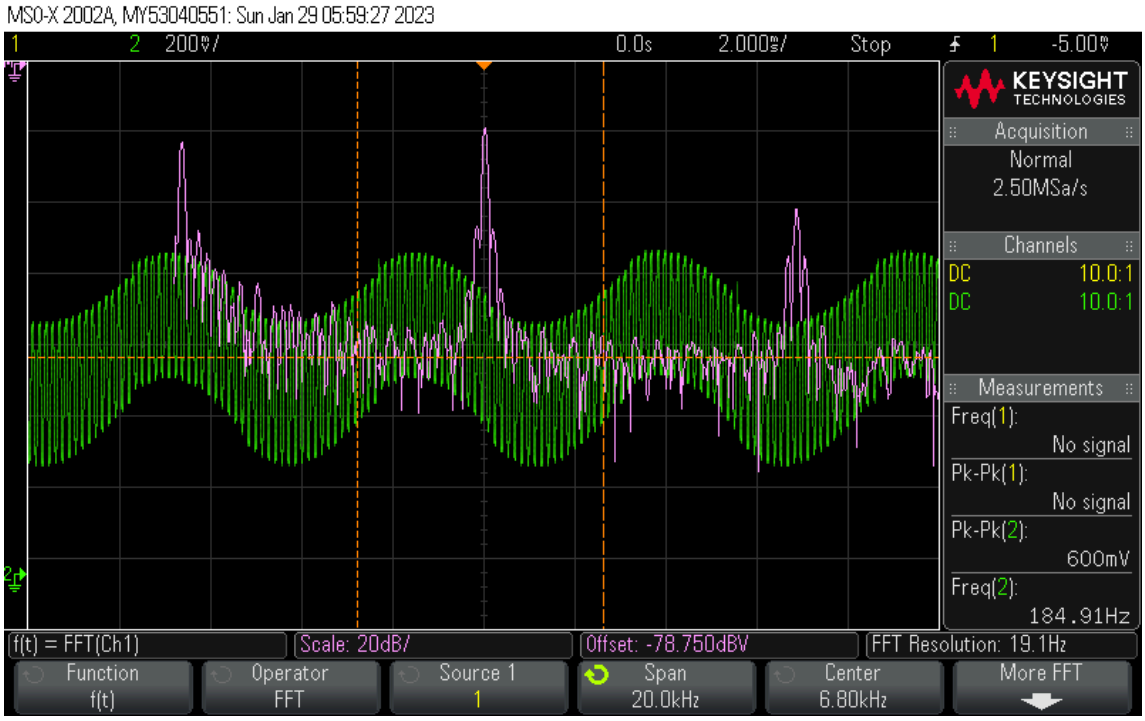

Fig.31 Mixer Output

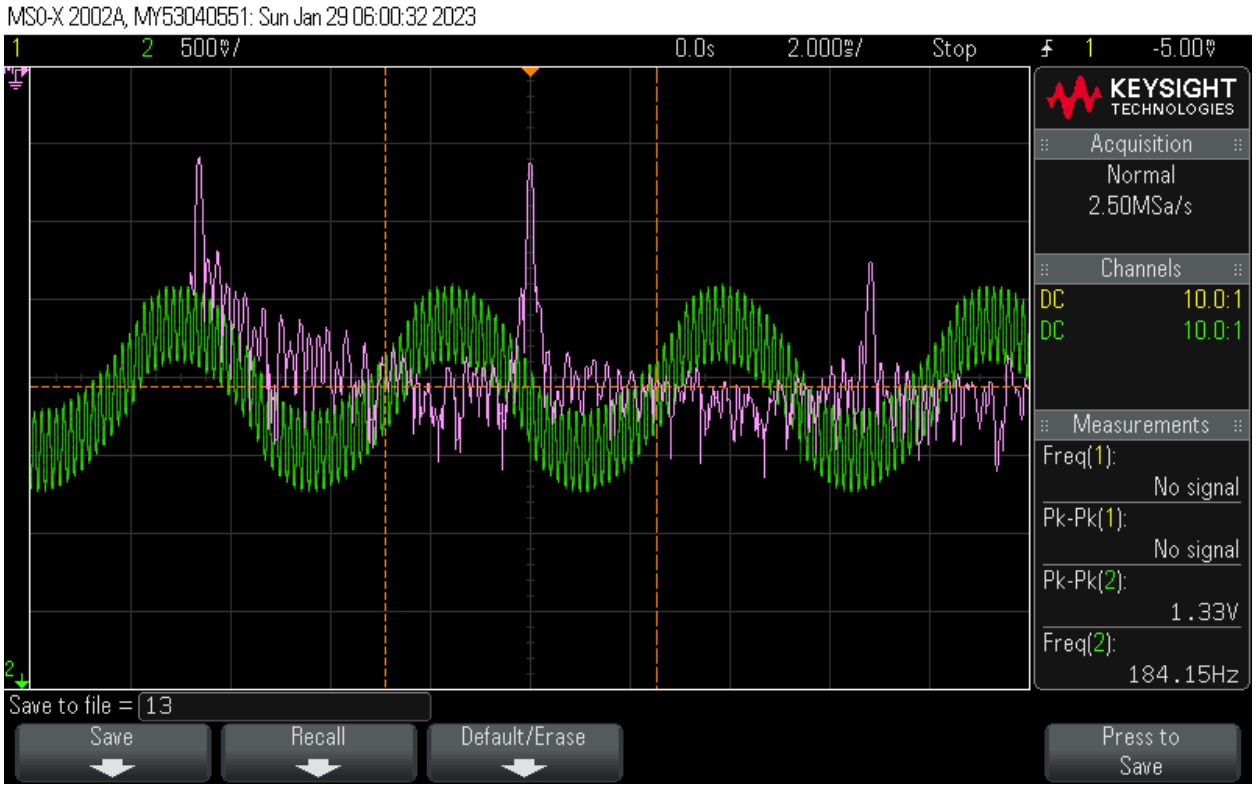

Fig.32 Filter Output

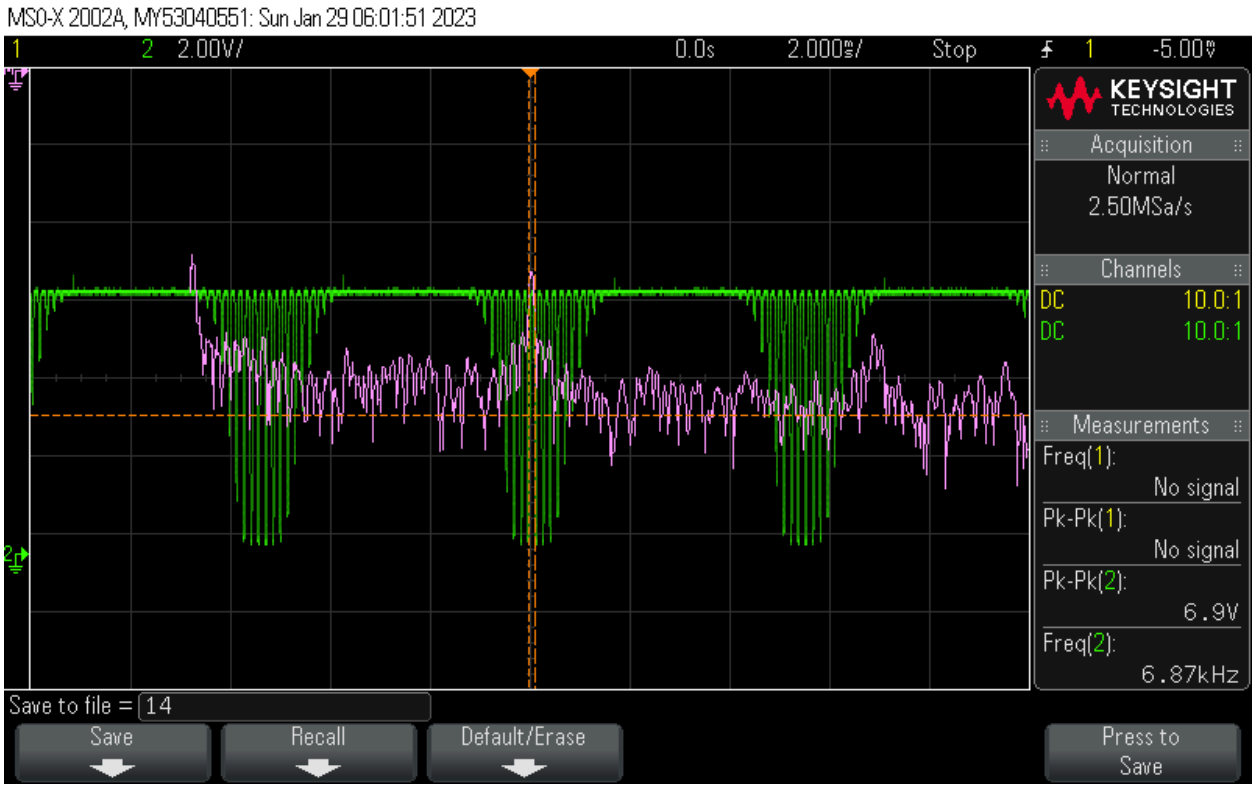

Fig.33 Amplifier Output

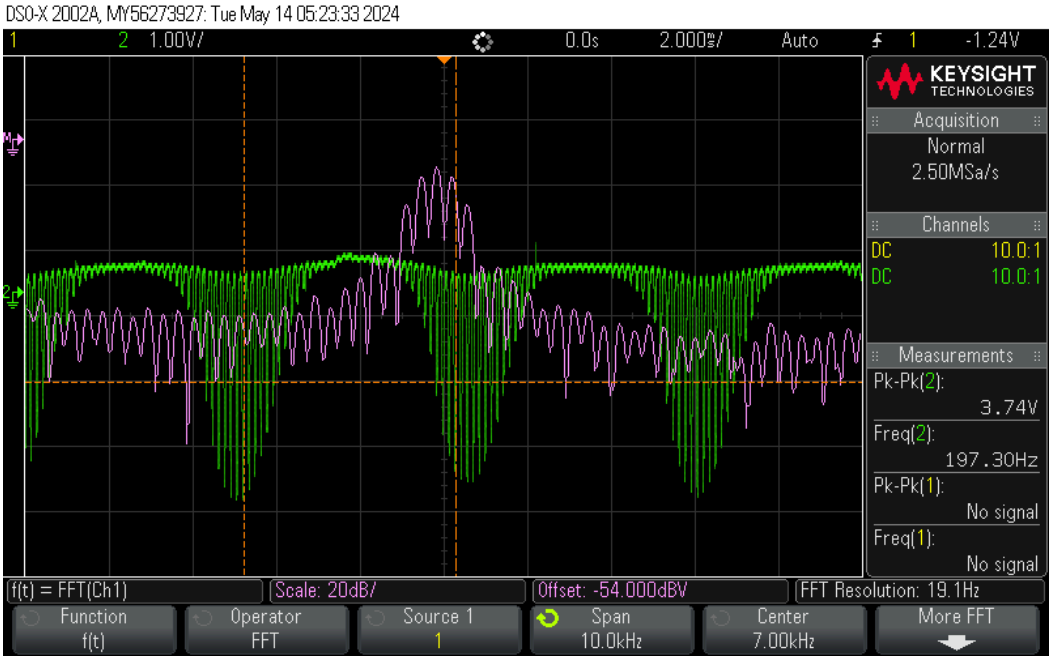

Fig.34 Output Stage Output

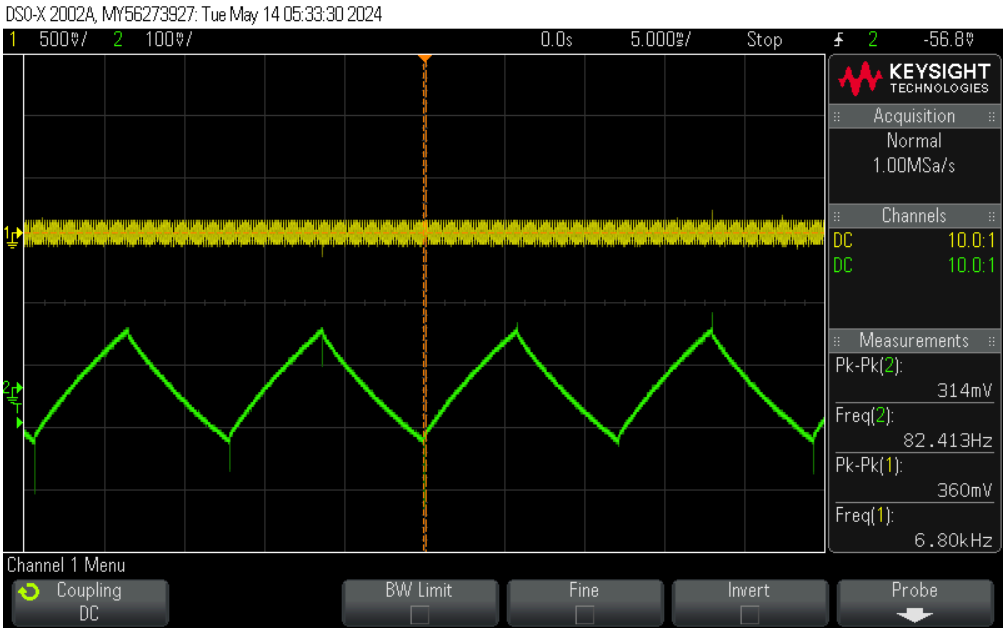

Fig.35 Second Set Input Waveforms

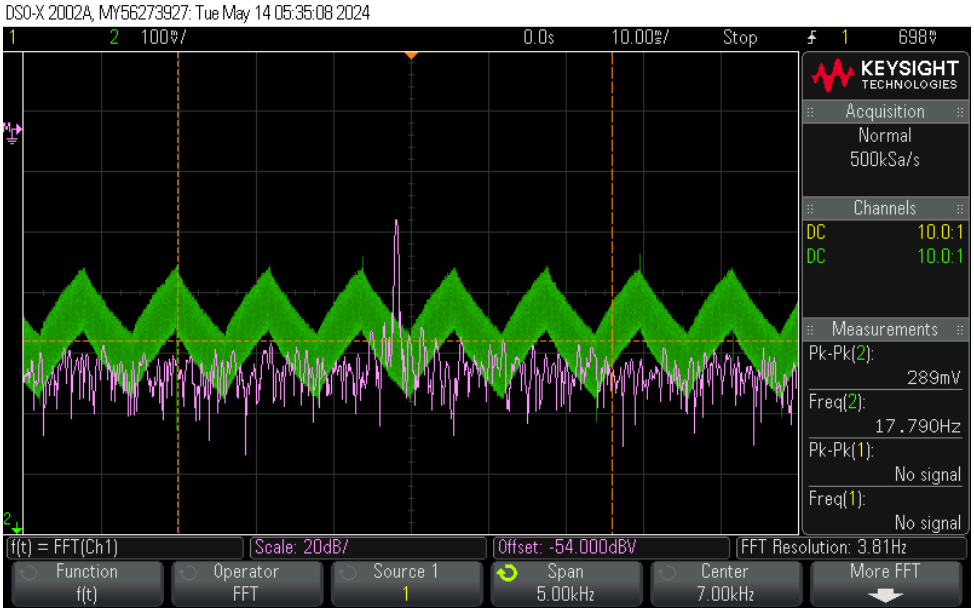

Fig.36 Mixer Output

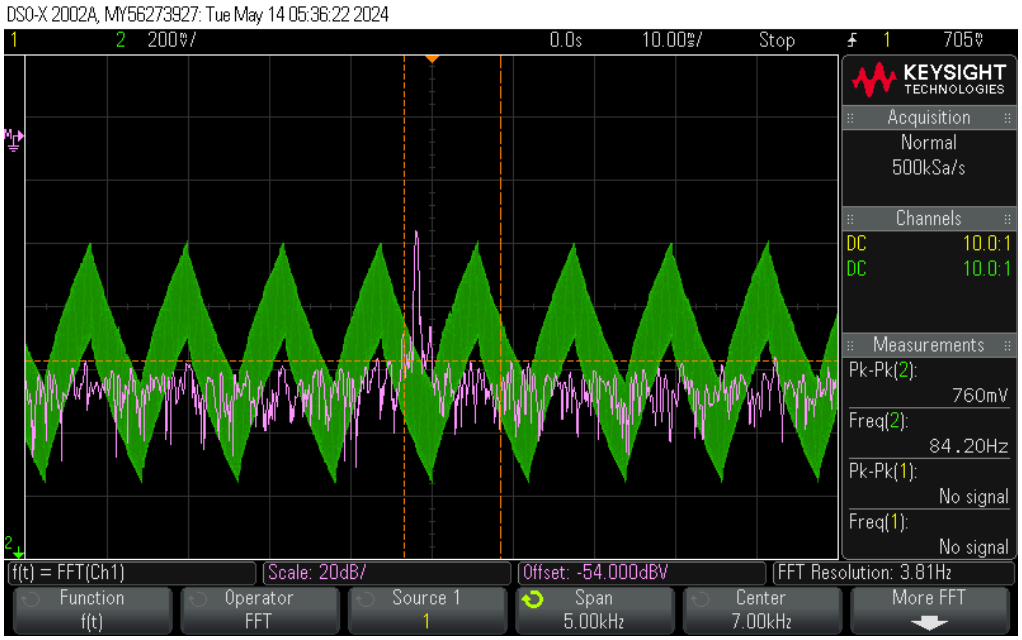

Fig.37. Filter Output

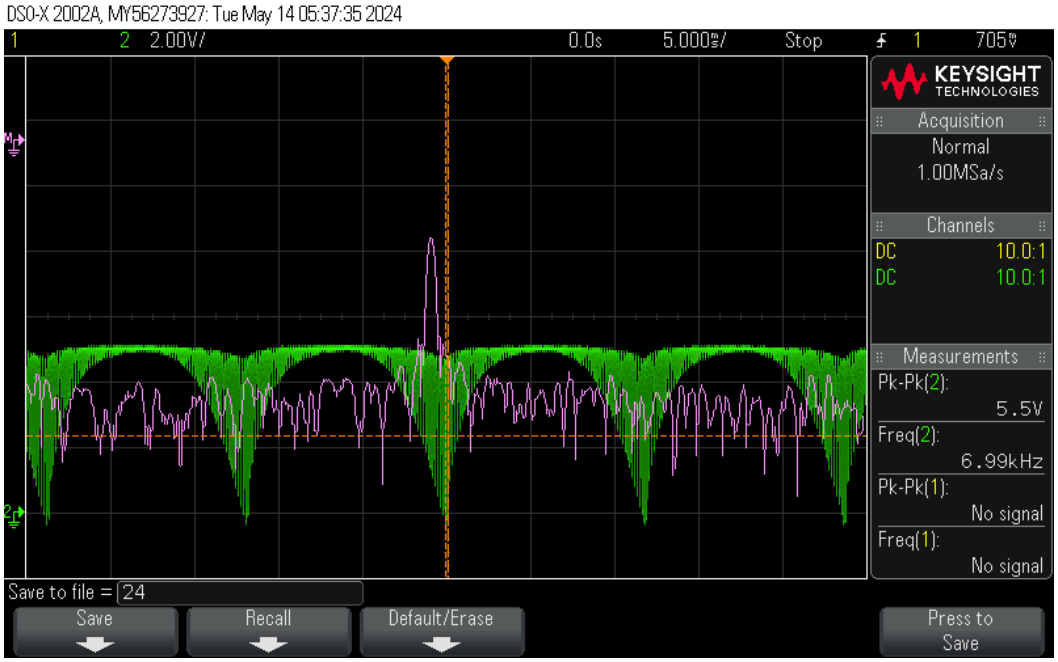

Fig.38 Amplifier Output

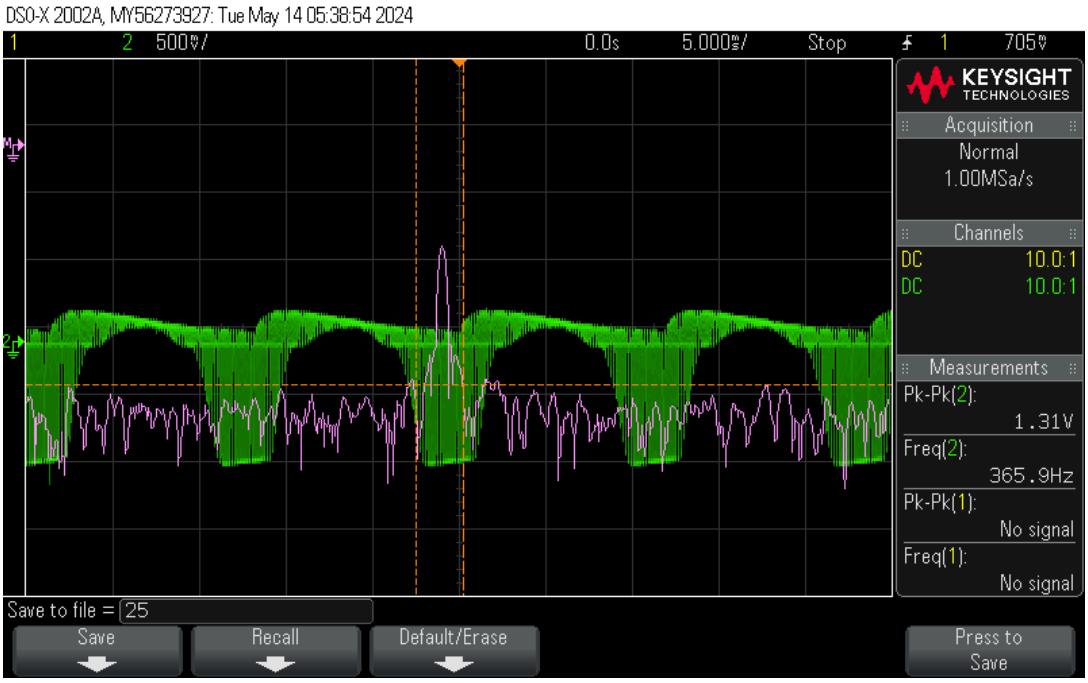

Fig.39 Output Stage Output

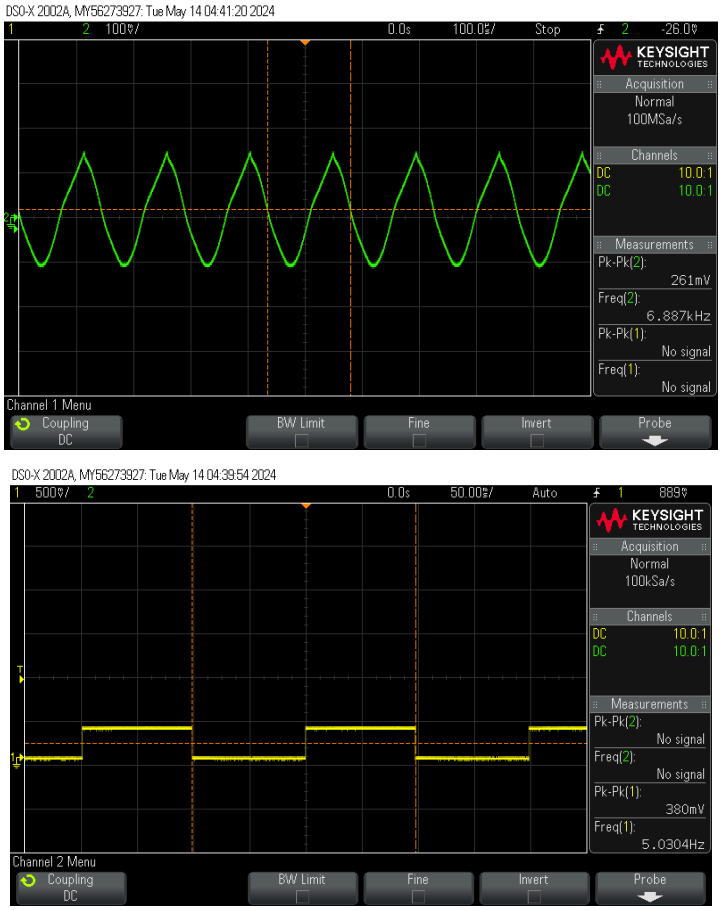

Fig.40 Third Set Input Waveforms

Fig.41 Mixer Output

Fig.42 Filter Output

Fig.43 Amplifier Output

Fig.44 Output Stage Output

Discussion:

- Midterm Design Choices
  - For the mixer stage of the circuit, we used the Practical Diode Mixer. We changed the value of the resistor after the diode to achieve a high

harmonic distortion in LTspice simulation. The reason for a high harmonic distortion is to make the output sound more pleasant (in our minds at least).
    - When it comes to the filter stage, we went with the 4th order Sallen-Key because we wanted a significant dropoff in gain at the 3DB point (cutoff frequency). We chose a 4th order low pass because we want the dropoff gain to be fast, and we wanted it in an active Sallen-Key configuration because we wanted to isolate the filter from the rest of the circuit. The active LM741 op-amp is the reason this is possible.
    - For the amplifier portion of the circuit we used NPN BJTs to save on cost and to exercise our knowledge of transistor circuits.
- Midterm Implementation Tradeoffs
    - The main tradeoff we had encountered was due to the limited supply and diversity of components we had access to. Perfect values could be found at online vendors but due to the cost of shipping a few discrete components, we opted to settle for components that were near the values we needed.

- Midterm Experimentations
    - Throughout the testing process, we were implementing a 15Ω buzzer. We were using this to test the performance of our circuit from sweeping frequencies and amplitudes. We never relied on a specific set, we just tested in a wide range of amplitudes and frequencies to see the variation we could get in the audio output. Over time, we saw that there was more and more of a change in the output of the buzzer as we continued to update the circuit blocks.

- Final Design Choices
    - LFO
        - A 555 timer connected to 2 integrator stages would give us the output waveforms and frequencies we desired; square, triangle, and sinusoidal.
    - HFO
        - A Wein Bridge oscillator was chosen to output a high frequency sinusoidal waveform.
    - Output stage
        - We decided to choose a class AB output stage as it has a good balance between power efficiency and
- Final Implementation Tradeoffs
    - The integration stages of the circuit for the LFO had to have a potentiometer in parallel with the capacitor that was connected to the inverting terminal and the output of the OP amp because the waveforms

did not stay consistent with the applied frequencies. In the final design of the filtering stage, we decided to implement capacitor values that did not meet the perfect design criteria for the selectivity we wanted; this frequency response can be seen in the FFT plot for the filter stage. To fix this we would have had to buy two 75 nF capacitors and due to budget restraints, we opted to use two 100 nF capacitors.

- Final Experimentations
    - While working through the development of our white noise generator, we went through two different configurations. Initially we experimented with the short form model, but it was only operational at 24V, and the output was not up to our standards. We moved to the larger model, but modified it to be smaller (see figure 16). This configuration was operational at 12V and produced a much larger noise signal.

Conclusion:

After completing the required experiments and designs for the last portion of the synthesizer, there are still small changes that could be made before beginning the process of designing the oscillation portion of the circuit. We must make sure that the blocks behave fully as expected when combined. Once the mixer, filter and amplifier are fully functional, the project will behave much better and perform to our full expectations. The most challenging part of the project thus far is designing the circuit around the components that we have available to us. Due to the nature of the operation of the Sallen-Key Lowpass filter, finding values for capacitors was challenging and if the values were not close to exact, the filter would behave too far outside of our specifications. Other than that, we are excited to continue this circuit, and to see how we can improve these important stages. As we moved on, we were able to design and test many different blocks working together in this comprehensive design. We learned that layout and spacing is very important when making a multistage project such as this. Without proper spacing we could easily run out of room on our breadboards, making it difficult to test and measure. We also learned more about the miller integrator configuration for outputting different waveforms. Our experience with implementing and integrating all stages of the complete synthesizer proved to be challenging but the experience we gained in troubleshooting and implementing simulated circuits was well worth the effort and we are satisfied with what we were able to accomplish in this course.

----------END OF REPORT----------