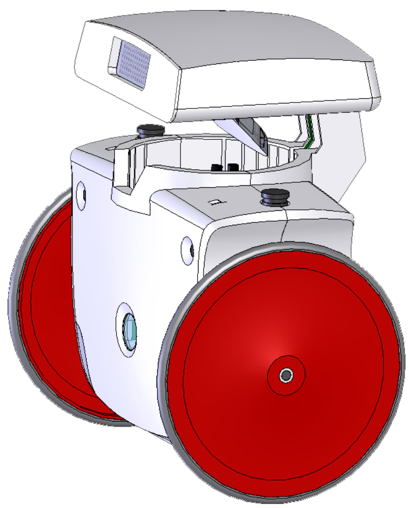
Boston University

Electrical & Computer Engineering

EC464 Capstone Senior Design Project

Customer Installation Report

Better Bots



by

Team # 15

Team Hazy

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1 Details of Customer Installation

Date of installation: 04/26/2023
Location of installation takes place: Zoom & PHO 113
Members present: Haoyan Zhang, Yidi Wu, Zhengyi Yang, and Alejandro Roberto
Customer present: Daniel B. W.

For the customer installation will be a report based on the areas our team had improved over the semesters. To evaluate and enhance the circuits that our customer has created, our team decided to use the AM-Radio Localization subsystem in the robot for this project. The project will mainly rely on prototyping using LTspice and simulating on it to validate the simulation findings. The improvement of the system will mainly take place on Zoom or Lab hours and the validation of the prototype will take place at PHO 113.

2 Introduction

The overall objective of this project is to implement and improve the existing AM Radio Localization subsystem shown in Fig.3. The AM Radio is composed of seven different components. Low noise amplifier (LNA) that will amplify signals coming from the active antenna while degrading the signal-to-noise ratio. Tracking filter is a bandpass filter that will pass only a narrow range of signals coming from LNA according to the AM station. Phase locked loop (PPL) along with voltage control oscillator (VCO) will generate an oscillator from 0.5MHz - 1.6MHz with a step of 10KHz from the computer. A triode mixer produces an intermediate frequency signal by multiplying a radio frequency with a local oscillator frequency signal. Lowpass filter removes all the unwanted noise of the intermediate frequency. The last part is a hard limiter that will transform all the signals into a square waveform of 1.8V for the FPGA to measure.

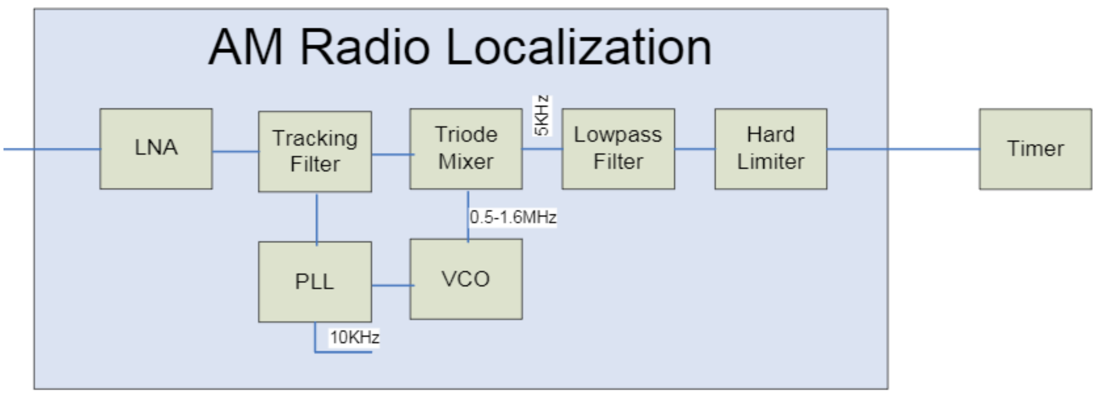

Fig.2-1 AM Radio Localization Modules

In the designing process of AM Radio Localization subsystem, PLL and VCO need to generate an oscillator signal from 0.5 MHz to 1.5 MHz with a step of at least 10 KHz and be able to adjust by computer control. Another requirement is that The mixer is what produces the 5KHz signal. Q-enhancement is used for the tracking filter and VCO. Q-enhancement takes positive feedback. We have to be careful with the level of positive feedback in order to not turn it into an oscillator.

Another goal is to limit the space of the AM Radio Localization circuits to a maximum of 3 square inches of a double-sided, 4-layer PCB will significantly help us to reduce the capacity. The final product will be designed with mostly discrete circuitry and open-source hardware design. Lastly, the AM Radio Localization should be comparable or higher quality than the current marketing AM Radio designs.

3 Active Antenna

Introduction of Active Antenna:

Unlike the other modules of the prototype, the active antenna is a new and original circuit to help our testing since the robot already has another complex system for collecting surrounding AM signals. The input of the active antenna is connected to a 15 feet 28 gauge wire, and the output of the active antenna containing all the AM signals will then be filtered and detected by the rest of the system.

Brief description of Active Antenna:

Fig.3-1 illustrates the schematic active antenna circuit, powered up by a 3.3V DC source. The circuit consists of two stages. The first stage utilizes a BF256B JFET emitter follower with a voltage divider at the base to regulate the voltage at Output1 and prevent the JFET from saturating. The second stage of the circuit is a PN2222A BJT emitter follower to achieve a low output impedance. Since the spectrum analyzer only has a low input impedance of 50 ohms, a large output impedance is added between the circuit and spectrum analyzer during signal analysis to prevent damage to the spectrum analyzer.

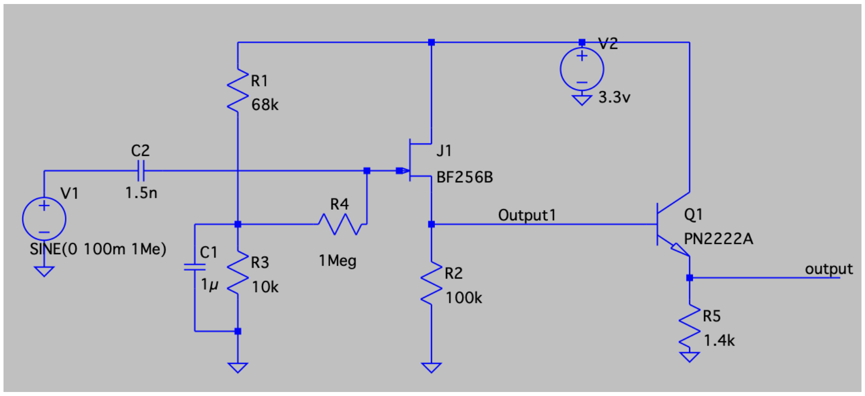

Fig.3-1 Schematic of Active Antenna

Simulation Output of Active Antenna:

As the bode plot of the output shown in Fig 2-2, the active antenna circuit will not amplify any signals. Instead, it will allow the signal in the range of 1kHz to 2MHz to pass through and attenuate the rest signals. This circuit is particularly useful for AM radio which covers frequencies ranging from 500kHz to 1.8MHz.

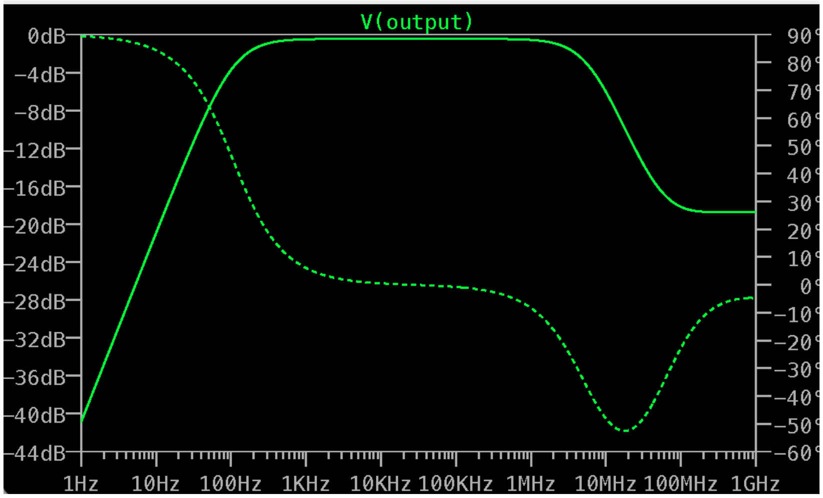

Fig.3-2 Simulation Output of Active Antenna

Testing Output of Active Antenna:

Fig.3-3 displays the prototype of the active antenna on a breadboard. By replacing the input with a 15 feet 28 gauge wire, the active antenna is able to collect the surrounding AM signals. Fig.3-4 shows the output of the active antenna on the spectrum analyzer, revealing the presence of AM radio signals in the Boston University Photonics Center Room 113. The room contains multiple AM radios, as indicated by the distinct peaks on the graph, notably at 850kHz, 1.03MHz, 1.32MHz, and 1.55MHz. The graph serves as evidence that the AM radio signals are capable of penetrating through the walls and being collected by the active antenna.

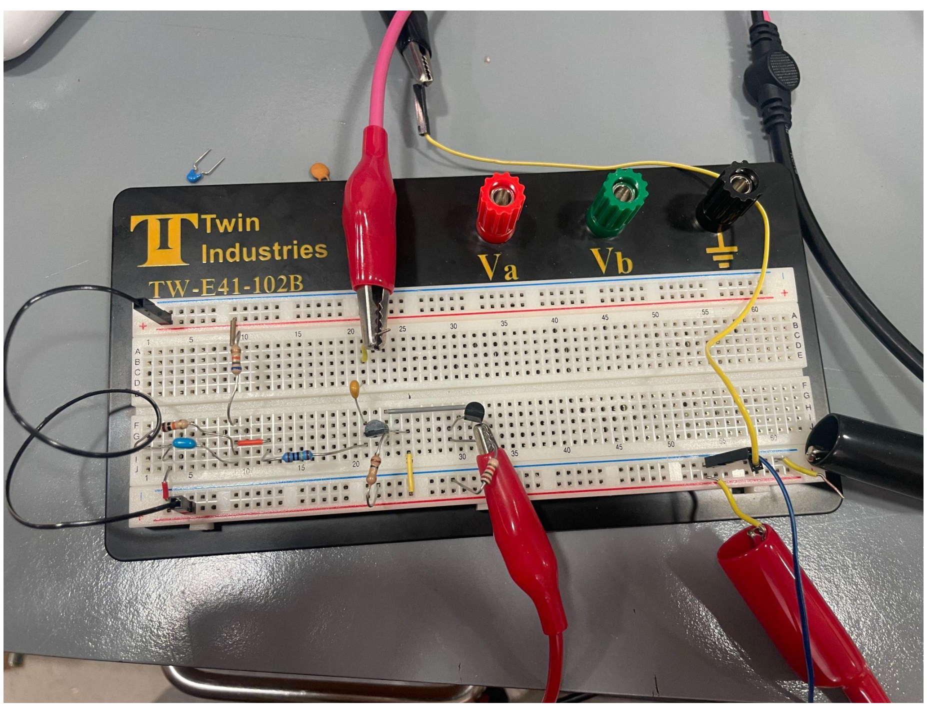

Fig.3-3 Active Antenna Prototype

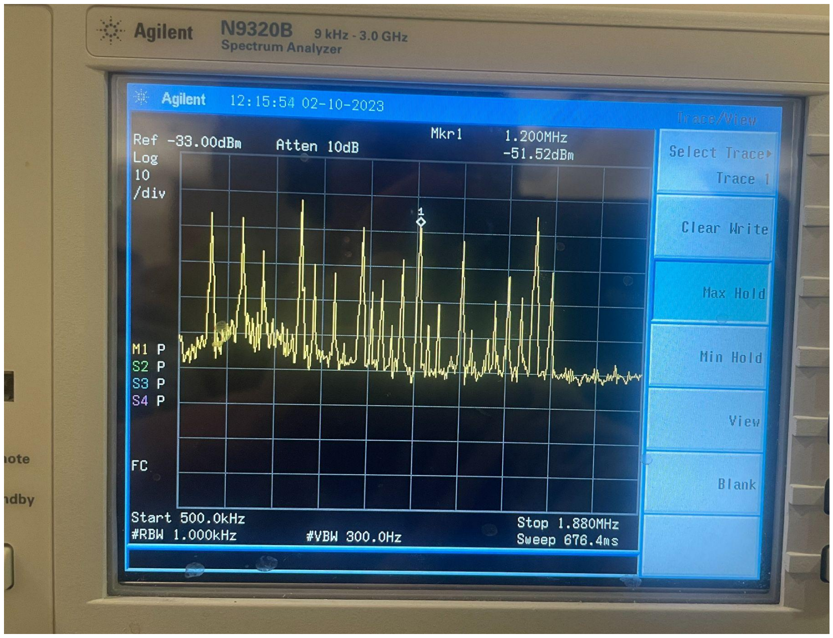

Fig.3-4 Spectrum Analyzer Output of Active Antenna

4 Isolation Amplifier

4.1 Original Version of Isolation Amplifier

Target Improvements:

The goal of this section is to improve the original version of the isolation amplifier, the areas we focused on were the gain, input noise, and input impedance of the isolation amplifier. The gain is the relationship between the input voltage and the output voltage of the signal, we measured in dB within our analysis. The performance of an isolation amplifier heavily depends on the noise, the noise is an unwanted signal that creates disturbance for signal processing. The input impedance of the isolation amplifier must be high.

Brief description of Isolation Amplifier:

The isolation amplifier in *Fig.4-1-1*, which is the first step in this signal processing chain, enhances the signal from the active antenna by a factor of 10, reducing the adverse effects of the following circuits as such. The isolation amplifier's gain should be precise and consistent across time, and the amplifier's bandwidth needs to be sufficient to accommodate the signal being measured frequency range, also the amplifier improves the signal-to-noise ratio of the AM localization system and prevents these disturbances from interfering with with with other systems which utilize the active antenna.

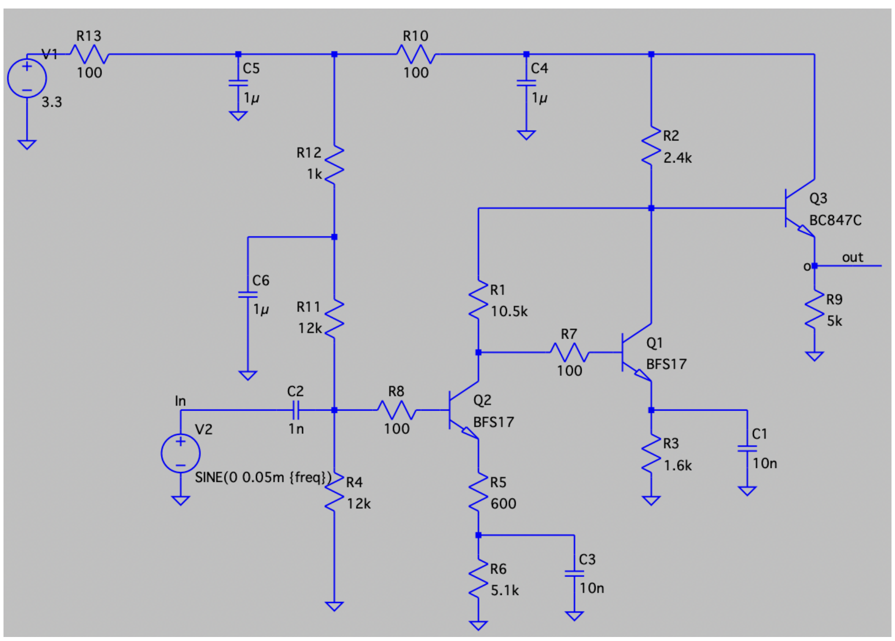

Fig.4-1-1 Original Isolation Amplifier Schematic

4.2 Improved Version of Isolation Amplifier

Brief description of the improved isolation amplifier:

The improved version of the isolation amplifier is shown in *Fig. 3-2-1*. The signal gain factor, input impedance, and reduced amplifier noise contribution will be the key areas of development for the isolation amplifier. We focused on R26 and R6 to improve the amplifier's gain because these two components would significantly impact the gain. The resistors R11 and R4 were subsequently modified to enhance the input impedance of the amplifier. Lastly, to reduce the noise contribution, R5 (referred to *Fig.4-1-1*) was the noisiest component of the amplifier, a solution to resolve this problem would be to reduce the resistance of R5.

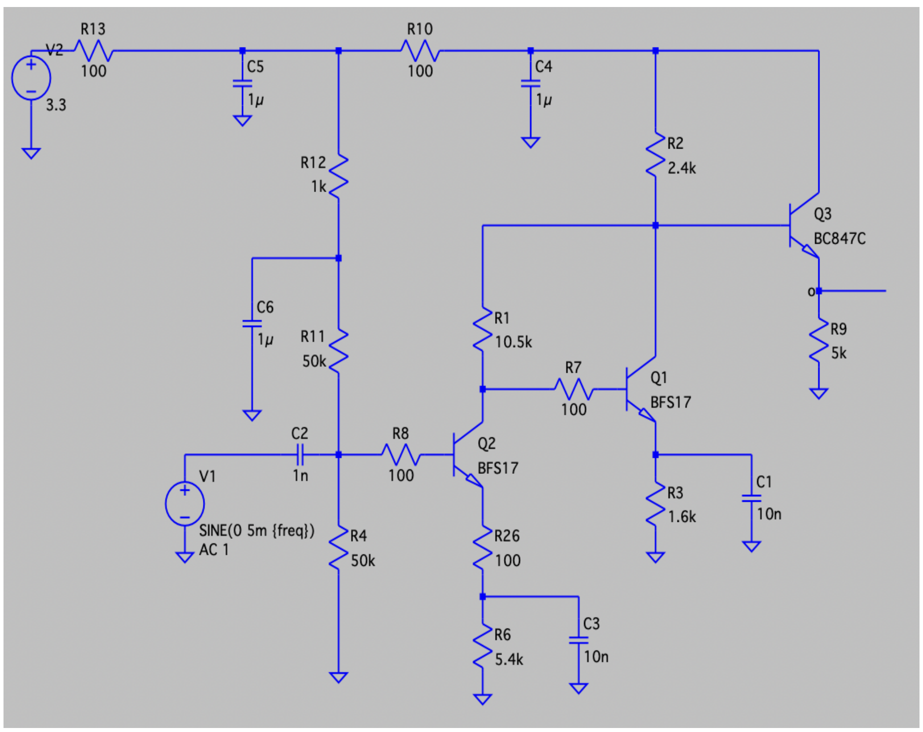

Fig.4-2-1 Improved Isolation Amplifier Schematic

Improving the input impedance:

In order to calculate the input impedance, we first need to calculate the base impedance of Q_2. In our circuit, the *Q_hfe* equals 300. The base impedance of Q_2 is Z_b. Then we plug this number into equation (1).

$$Z_b = Q\_hfe * R_{26} \quad (1)$$

$$R_{in} = (R_4 // R_{11}) // (Z_b) \quad (2)$$

$$R_{in} = (R_4 // R_{11}) // (Q\_hfe * R_{26}) \quad (3)$$

$$R_{in} = (12k\Omega // 12k\Omega) // (300 * 600\Omega) = 5.8k\Omega \quad (4)$$

Based on equation (3), the increment in $R_4$and R_{11} will increase the input impedance of the original circuit. Therefore, as we expect a higher input impedance. In the isolation amplifier circuit, R_4 and R_{11} functions as a voltage divider, setting a specific voltage of 1.55V at the base of the Q_2. To achieve this desired voltage, R_4 and R_{11} must have the same value. In the improved version of the isolation amplifier, both R_4 and R_{11} are set to 50k.

Referring to Equation (3) the improved isolation amplifier input impedance will be calculated in Equation (5) the improved isolation amplifier has a new impedance of 13.6kΩ.

$$R_{in} = (50k\Omega // 50k\Omega) // (300 * 100\Omega) = 13.6k\Omega \quad (5)$$

Improving the Tracking Filter sharp input impedance with INA:

The tracking filter has a sharp spike in its input impedance which could disturb other circuits that share the same active antenna. The isolation amplifier has a smooth input impedance and will protect other circuits. To compare the input impedance of the isolated tracking filter, original isolation amplifier attached to the tracking filter, and improved isolation amplifier attached to the tracking filter, we simply use an AC input to each circuit to simulate the input impedance which is shown in *Fig.4-2-2*, *Fig.4-2-4*, and *Fig.4-2-5*. In *Fig.4-2-3*, we can see that the input impedance of the original tracking filter is unstable near 1MHz, after placing the original and improved version of the isolation amplifier, we can see that the input impedance is much more stable than the tracking filter alone, which is shown in *Fig.4-2-6*.

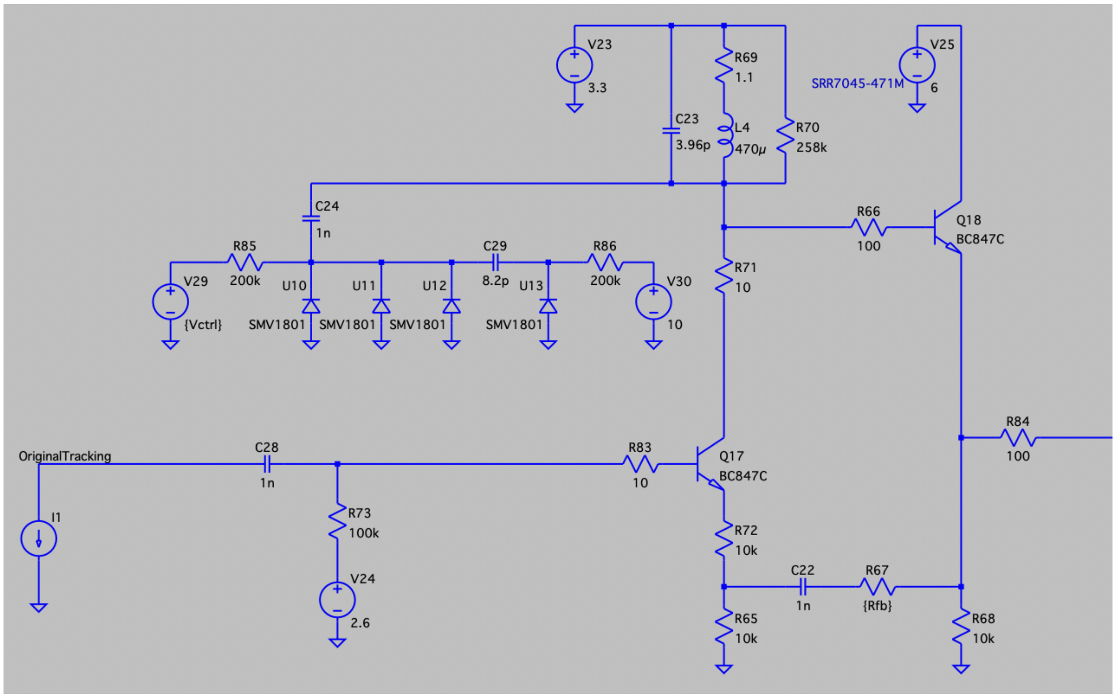

Fig.4-2-2 Original Tracking Filter with an input current source

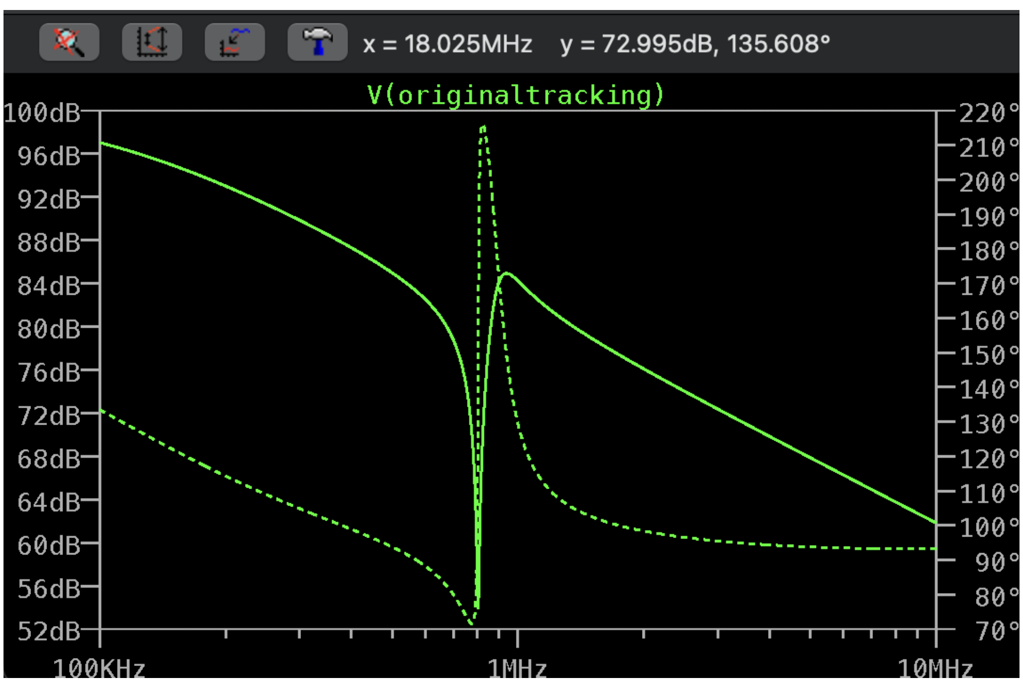

Fig.4-2-3 Original Tracking Filter input impedance

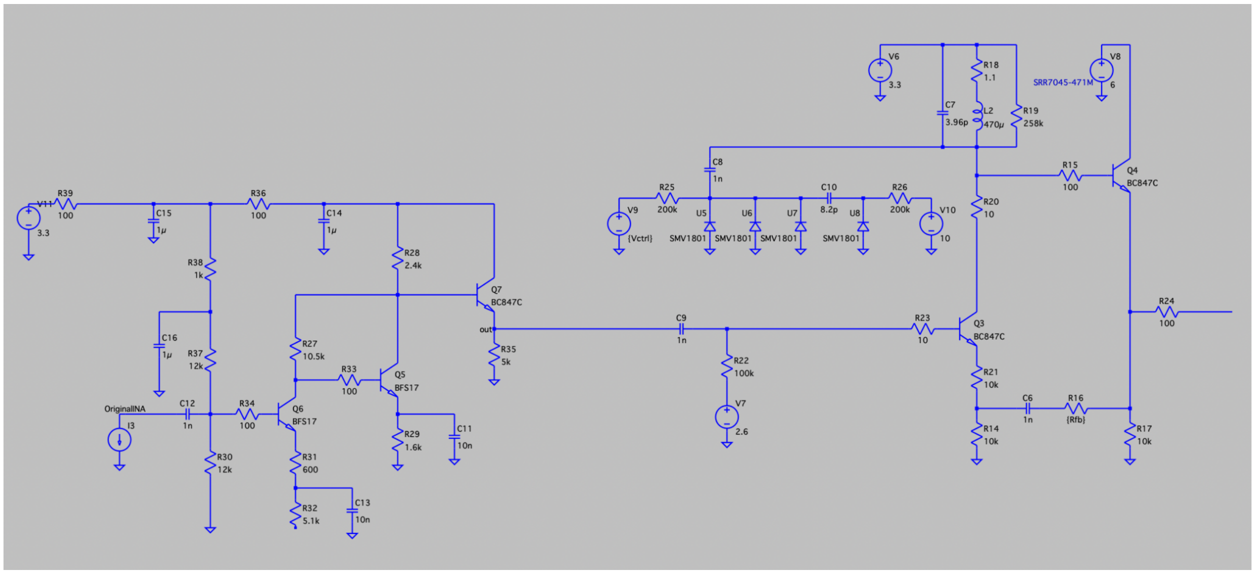

Fig.4-2-4 Original LNA attached to Tracking Filter with an input current source

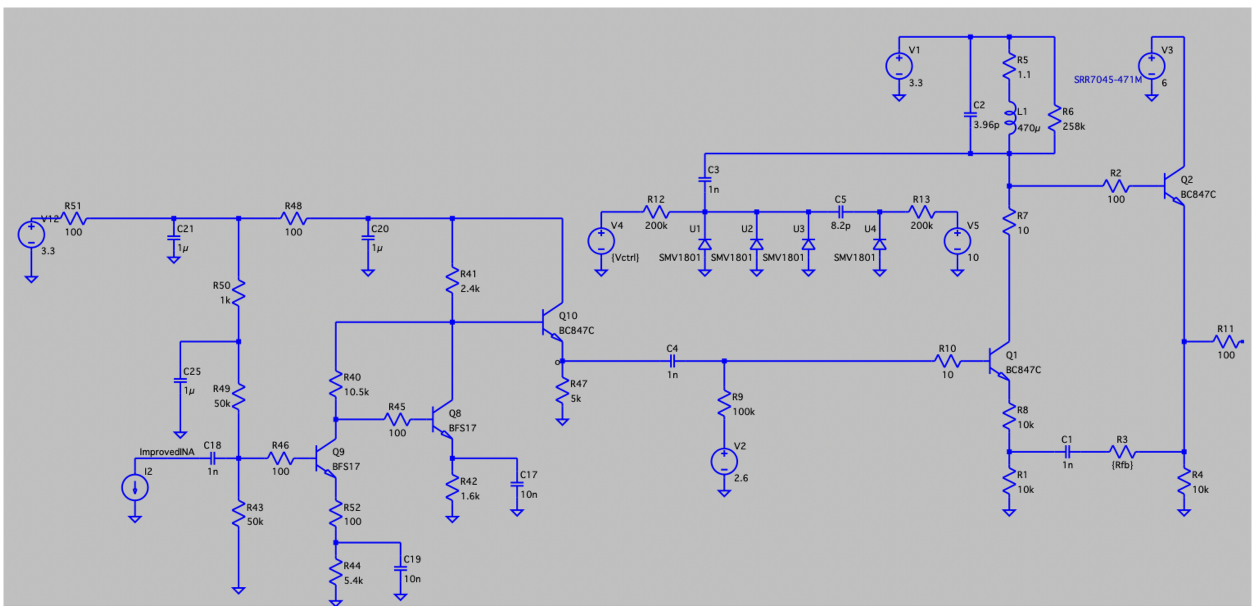

Fig.4-2-5 Improved LNA attached to Tracking Filter with an input current source

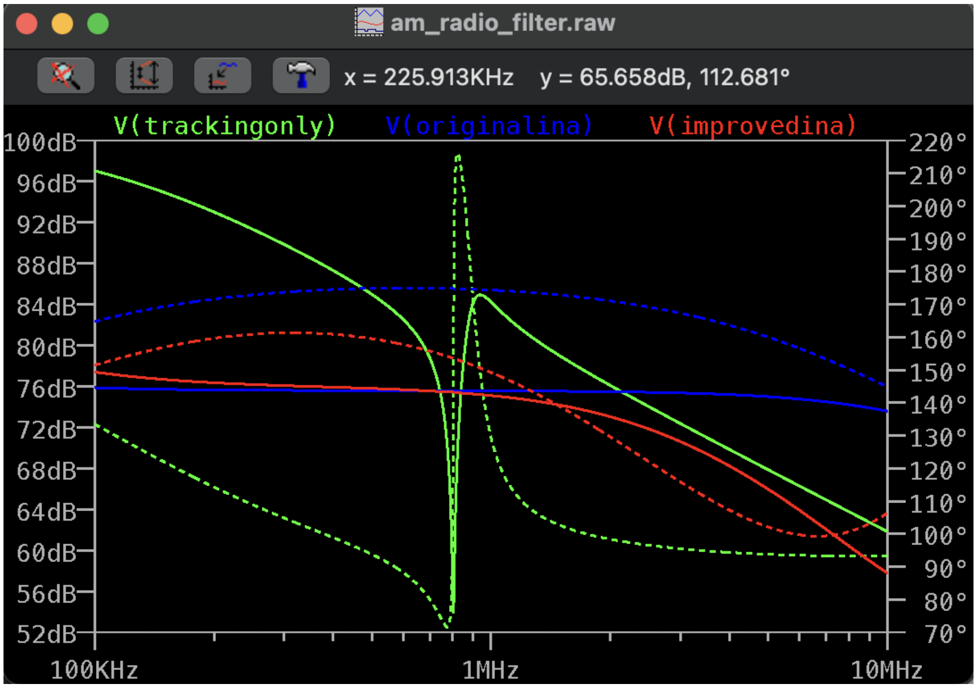

Fig.4-2-6 Original LNA attached to Tracking Filter with an input current source

Analysis of Simulation Outputs:

Compare *V(originallna)* with V*(improvedlna),* the magnitude in *Fig.4-2-7* has approximately 10dB increment. This indicates that the output signal of the improved isolation amplifier has approximately 3.1 times larger than the output signal of the original version isolation amplifier.

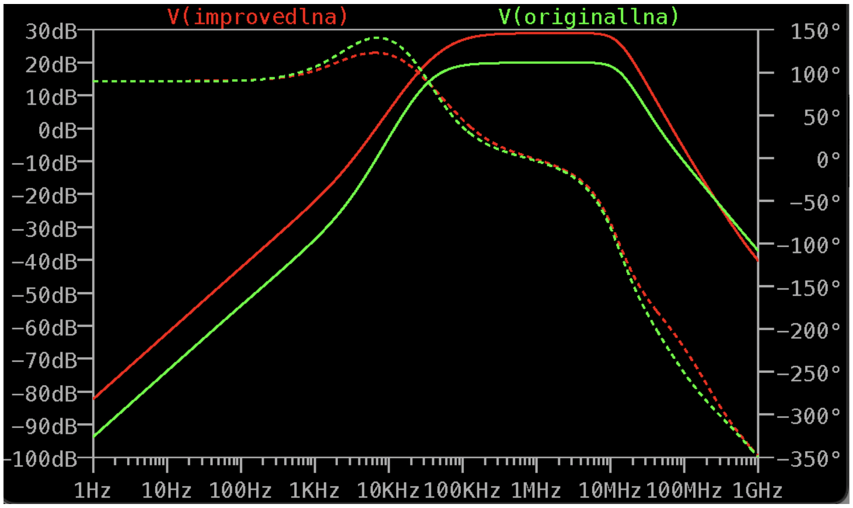

Fig.4-2-7 Bode plot of improved and original LNA

The input impedance of the amplifier will be critical, a high input impedance ensures quality signal transmission. The improved LNA has a higher input impedance than the original LNA before 1.5MHz shown in *Fig.4-2-8.*

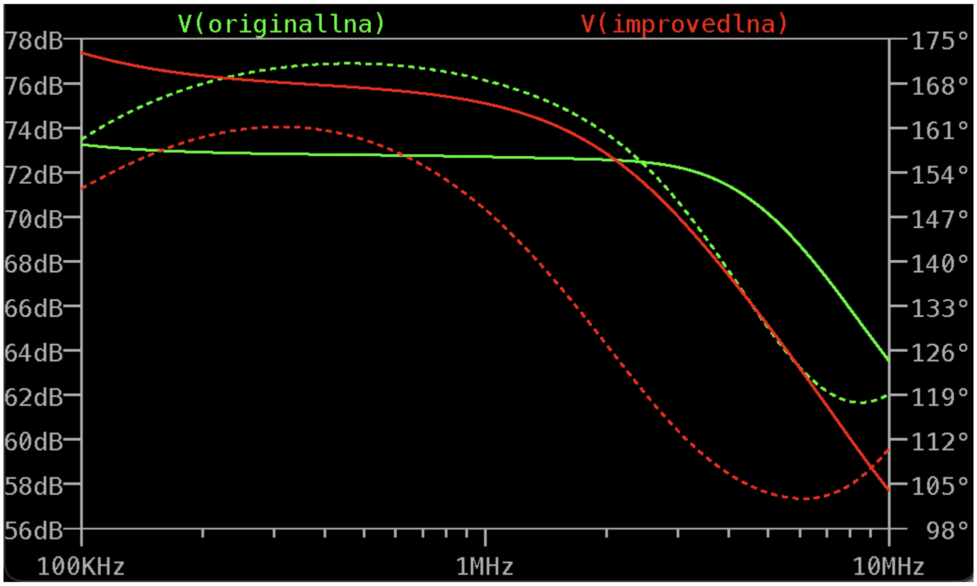

Fig.4-2-8 Input impedance impedance of improved and original LNA

The transient analysis shows how a circuit reacts to a time-varying input signal or shows how the circuit's output develops over time. The AC input in this case was set to a sine wave with 0.05mV and 1MHz. The input (V(in)) and output V(improvedlna) and V(originallna) signals are shown in *Fig.4-2-9* From *Fig.4-2-10* the improved LNA has a slightly higher peak voltage than the original LNA.

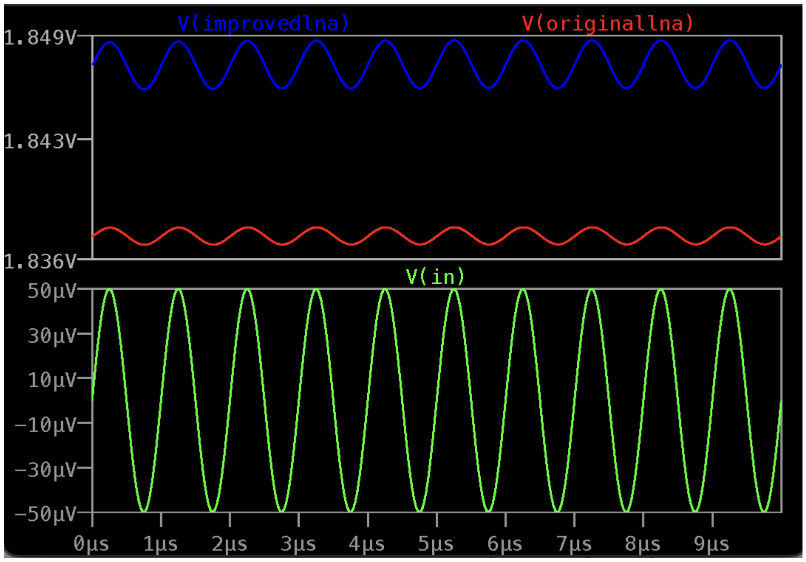

Fig.4-2-9 Improved and original LNA voltage waveform

The comparison between the input voltage noise is shown in *Fig.4-2-10*, from the graph, it's clear that the improved LNA input noise has been reduced by half amount than original LNA. The solution of reducing the noise of the circuit was to run a noise simulation in the Spice and determine which component has the highest noise contribution. In *Fig.4-2-11* shows the R5 has the highest noise contribution to the entire amplifier, to achieve a lower input noise we simply reduce the R5 value.

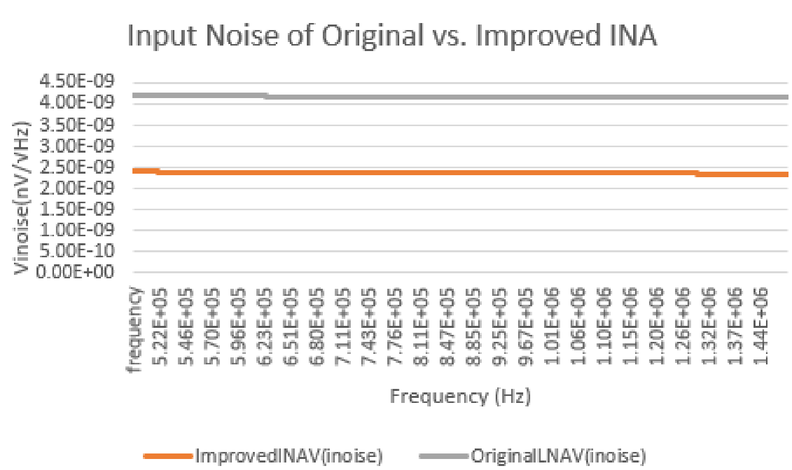

Fig.4-2-10 Input voltage noise of original and improved LNA

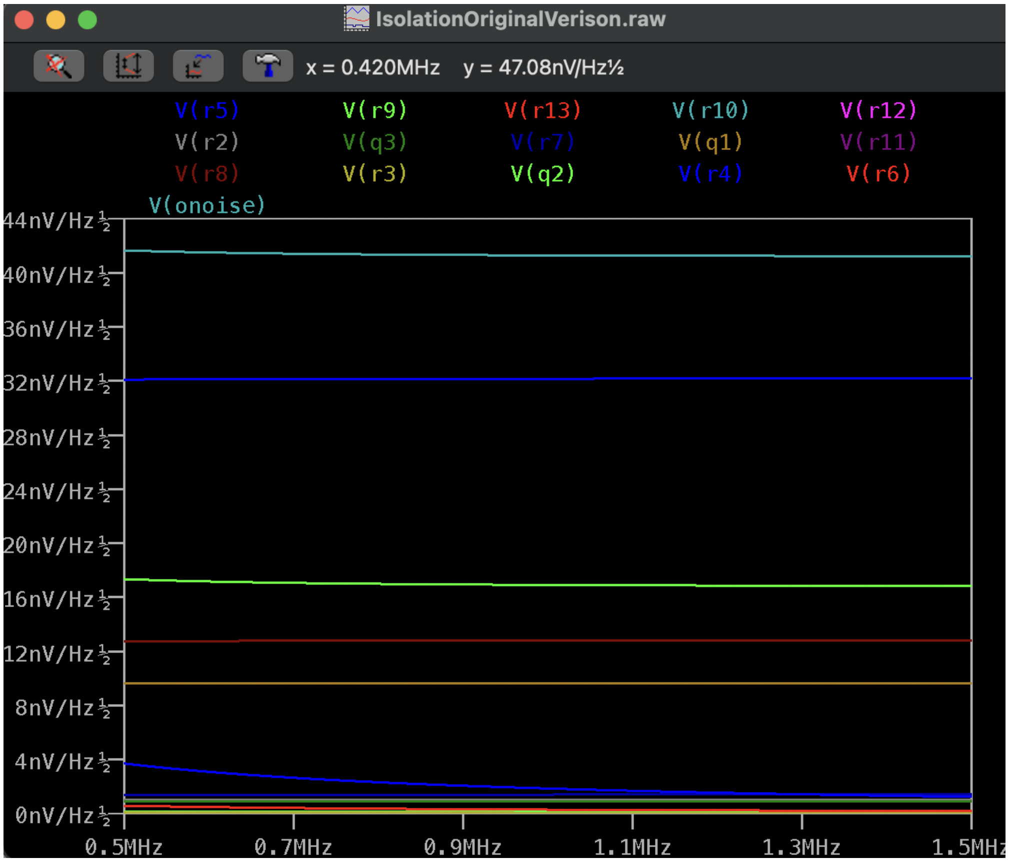

Fig.4-2-11 Contribution of each element to the output noise

4.3 Prototype Isolation Amplifier

Prototype isolation amplifier:

The prototype and the schematic of the isolation amplifier in *Fig.4-3-1* & *Fig.4-3-2* which is different from the improved isolation amplifier in section 3.2, the BFS17 transistor was replaced with PN2222 since BFS17 is currently off stock. There are some adjustments made with R1, R4,R5, and R10 to achieve similar behavior of the improved LNA in *Fig.4-2-1.* The implementation of this circuit uses only discrete components. A small value of resistors R6 and R7 will keep the transistors stable. R10 and R4 will increase the input impedance of the amplifier to prevent the circuit from overloading. Q2 will drive low impedance to Q1 this will eliminate the noise and generate a high-frequency response. Another important factor of an isolation amplifier is to amplify voltage gains, the signal gain factor is mainly dependent on R1 and R13. Q3 reduces the output impedance, which is required/recommended for signal amplification. This step is important because high output impedance will tend to result in loss of the signal and distortion.

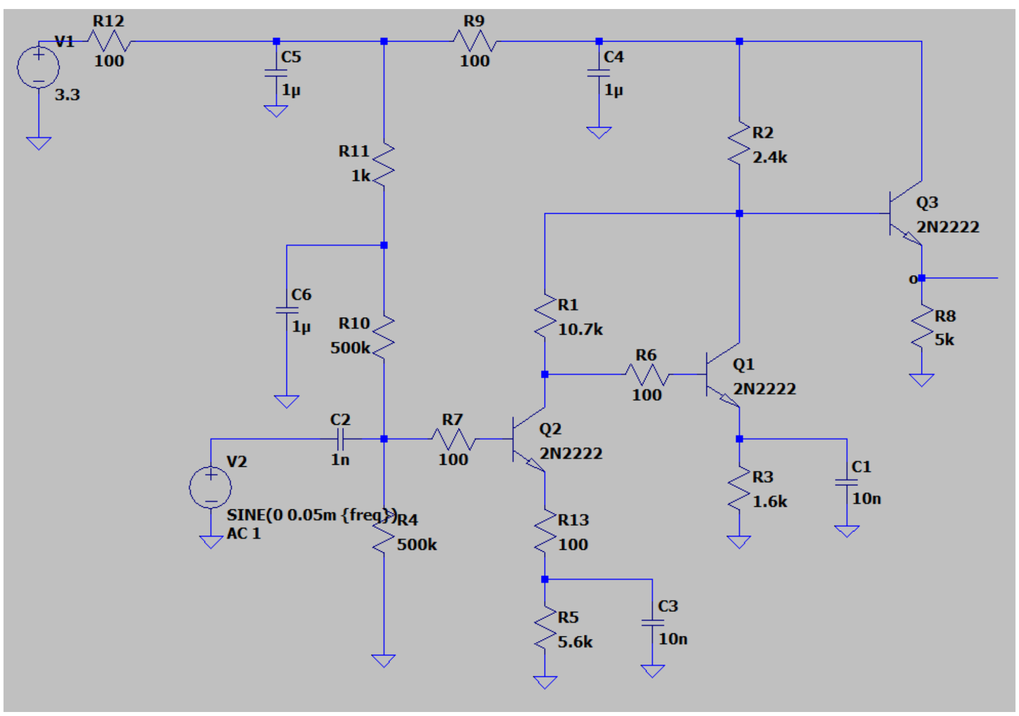

Fig.4-3-1 Schematic of the prototype LNA

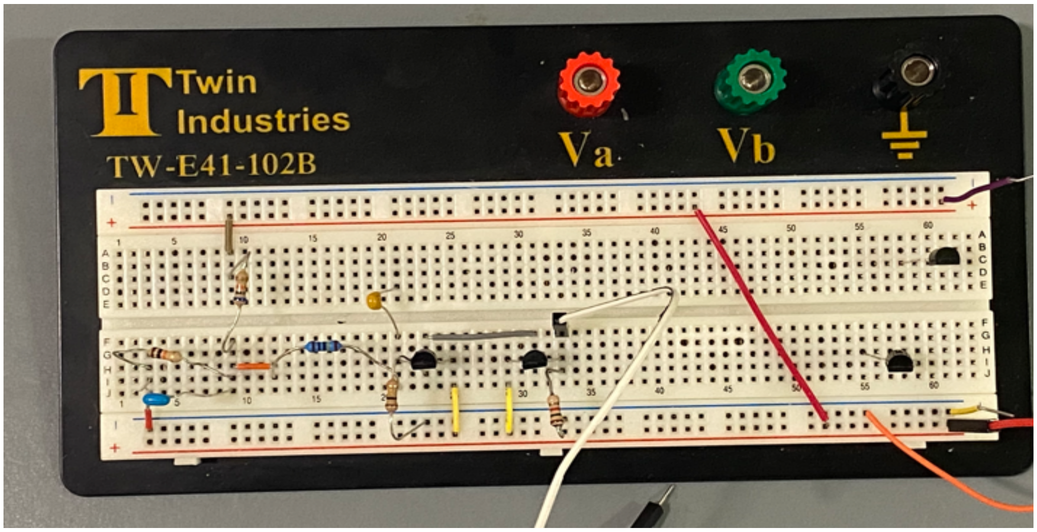

Fig.4-3-2 Prototype LNASS

Equipment and Setup:

To complete powering up and measuring the output gain of the isolation amplifier requires a power supply, function generator, and oscilloscope. The AC input is connected to the function generator with a frequency of 850 kHz. The DC input is connected to the power supply with 3.3V. Then we can check the gain by measuring the output voltage signal with an oscilloscope hooked up to the output end of the amplifier.

Simulation Results:

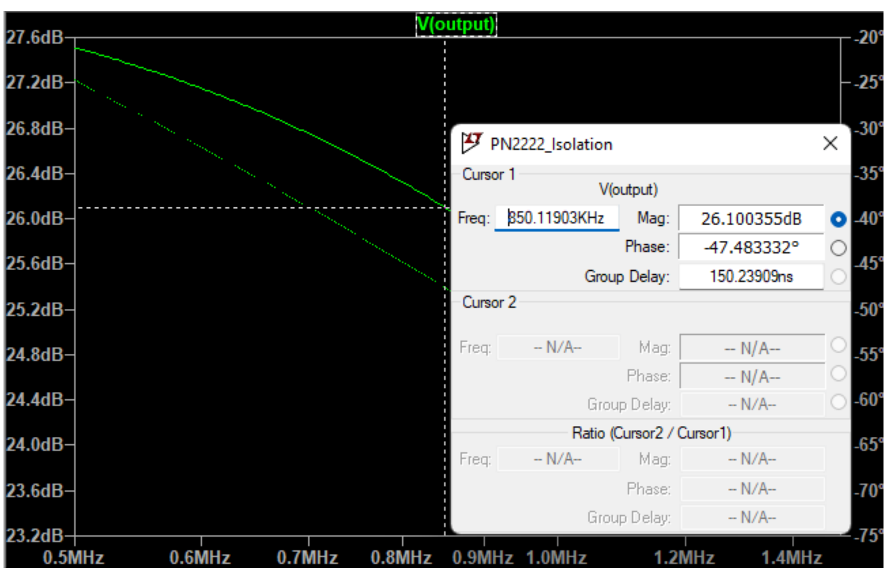

Fig.4-3-3 Voltage gain bode diagram of Isolation Amplifier from 500kHz-1.5MHz

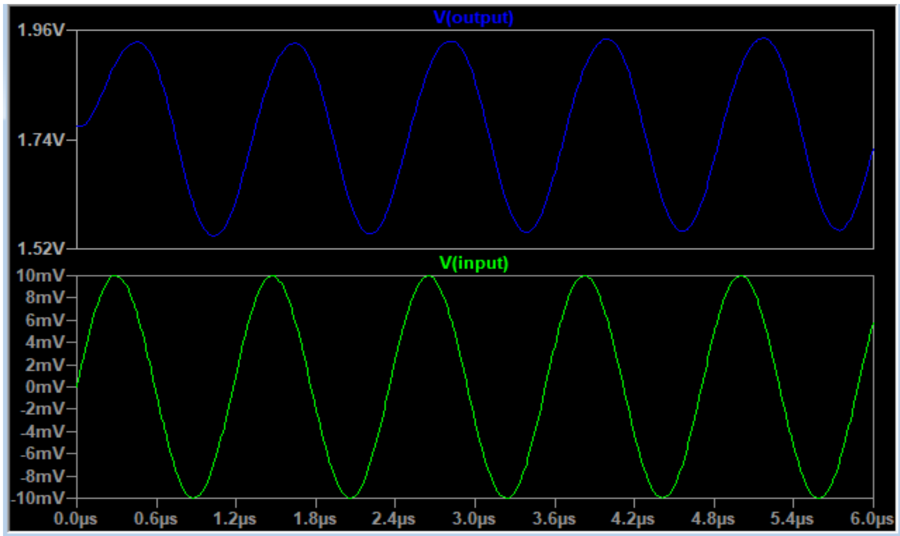

Fig.4-3-4 Transient Analysis of Isolation Amplifier with the input of 850 kHz & 10mV

Test Output/Measurements:

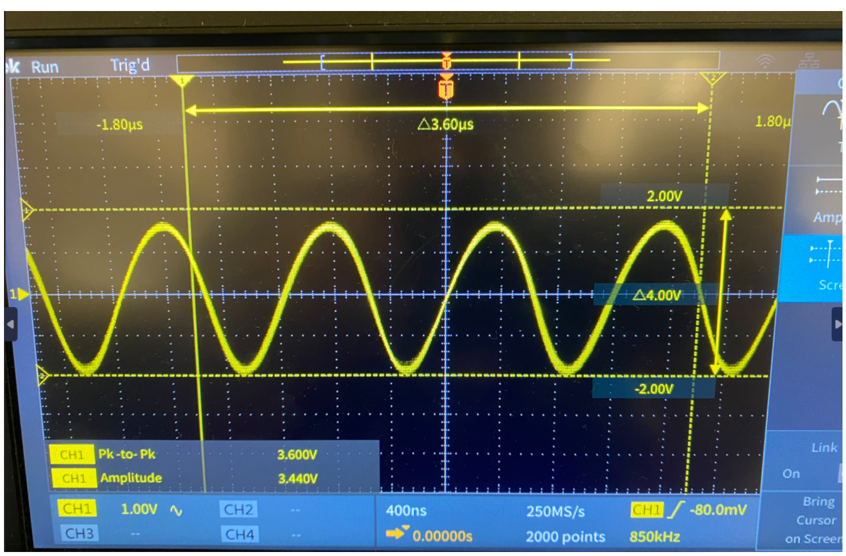

Fig.4-3-4 Isolation Amplifier Oscilloscope Output Waveform

The output generated by the isolation amplifier is within the range of our expected output. In *Fig.4-3-4* is the Voltage output from INA, we can see that the output with Pk-to-Pk of 3.6V, and our input amplitude is set to 10mV, this indicates the gain is 18. The expected gain range for our test plan is from 15-20. The isolation amplifier is working properly.

5 Tracking Filter

5.1 Original Version of the tracking filter

Brief description of the tracking filter:

Fig.5-1-1 Shows the original diagram for the tracking filter as provided by the client. S

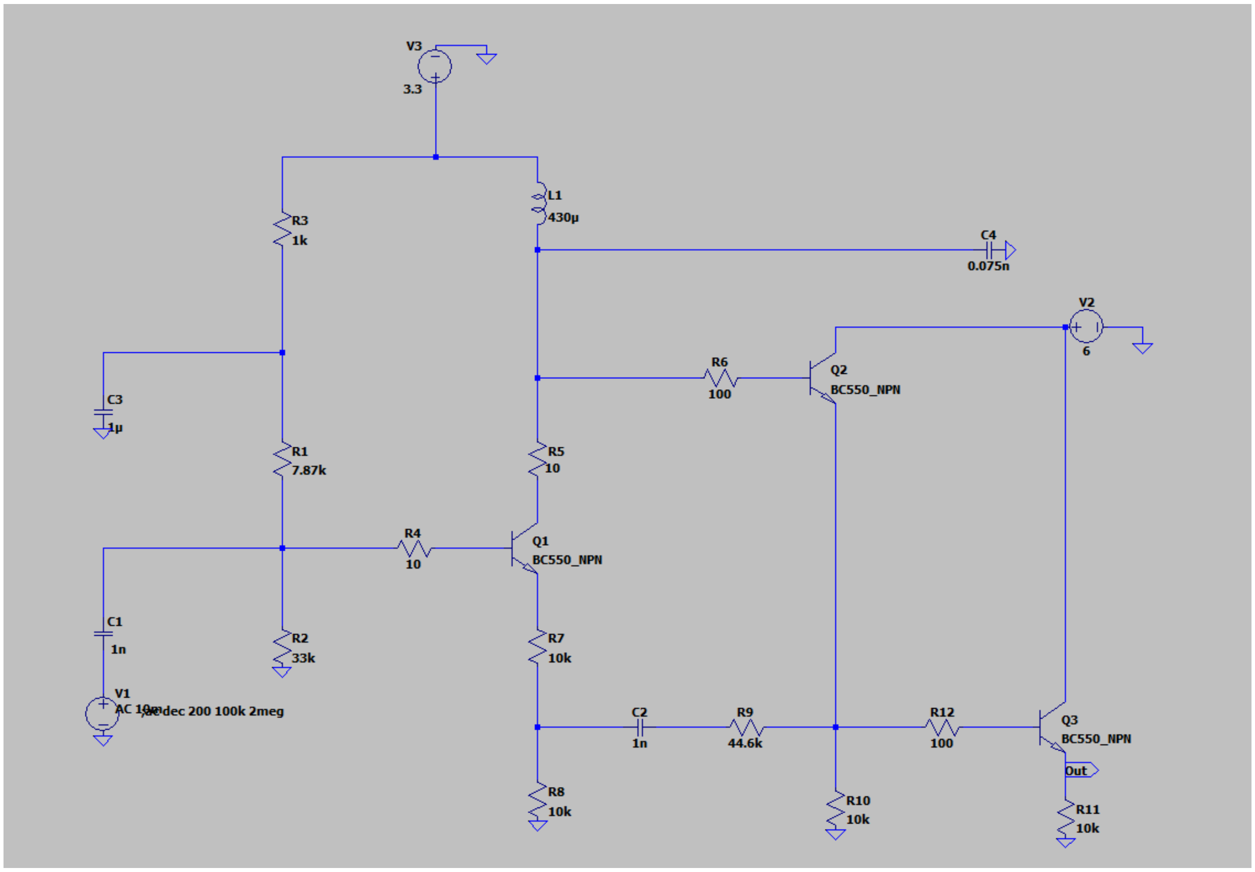

Fig.5-1-1 Original circuit diagram for tracking filter (Capacitor version)

Simulation Output of Original Tracking filter:

The following will be the gain of the filter at frequencies of 0.5MHz, 0.75MHz, 1MHz and 1.5MHz with an input of 10mVpp.

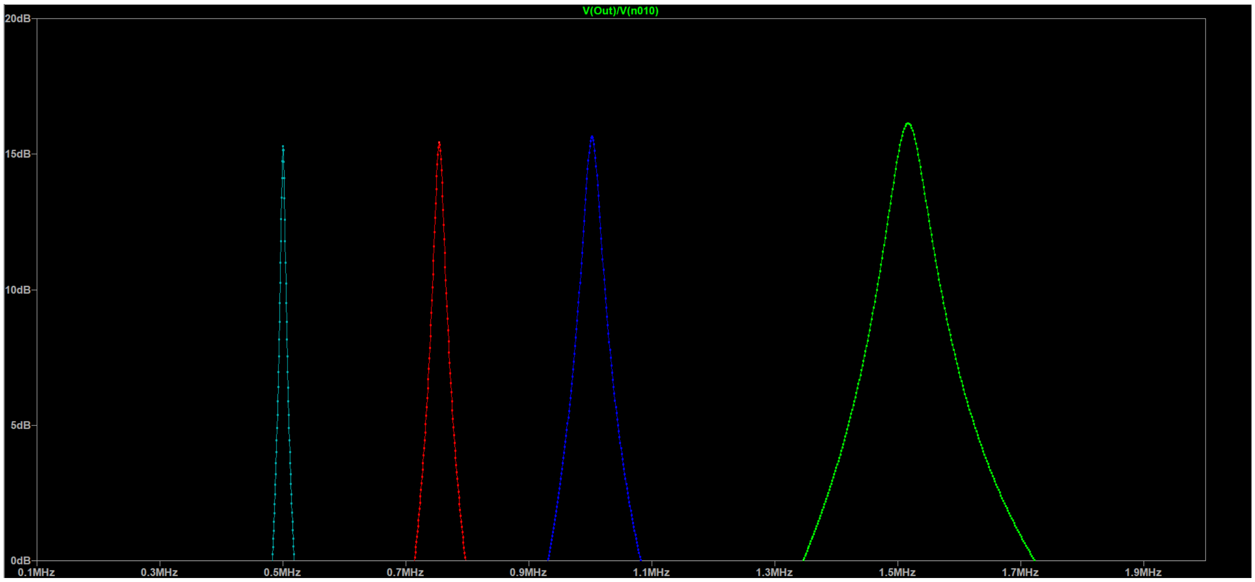

Fig.5-1-2 Original Tracking Filter Simulation Sweep

With every change in the frequency response, the Q of the filter also changes. For the previously shown Bode plots the bandwidth increases along with the magnitude of the target frequency, starting from a bandwidth of 6kHz at a 0.5MHz target frequency and increasing up to a 60kHz bandwidth at a 1.5MHz target frequency. In the case of the tracking filter a wider bandwidth is actually detrimental for the filter's performance, especially when considering that in highly populated areas AM radio stations are only separated by 5KHz.

Because of instability issues in order to make an actual comparison of the bandwidth at higher frequencies in the order of 0.9MHz we must change the value of R9 to 50.9kOhm, which gives us clues into what the improvement of the circuit will be. With the appropriate updates to the design we have an updated bandwidth of 22kHz at 0.9MHz.

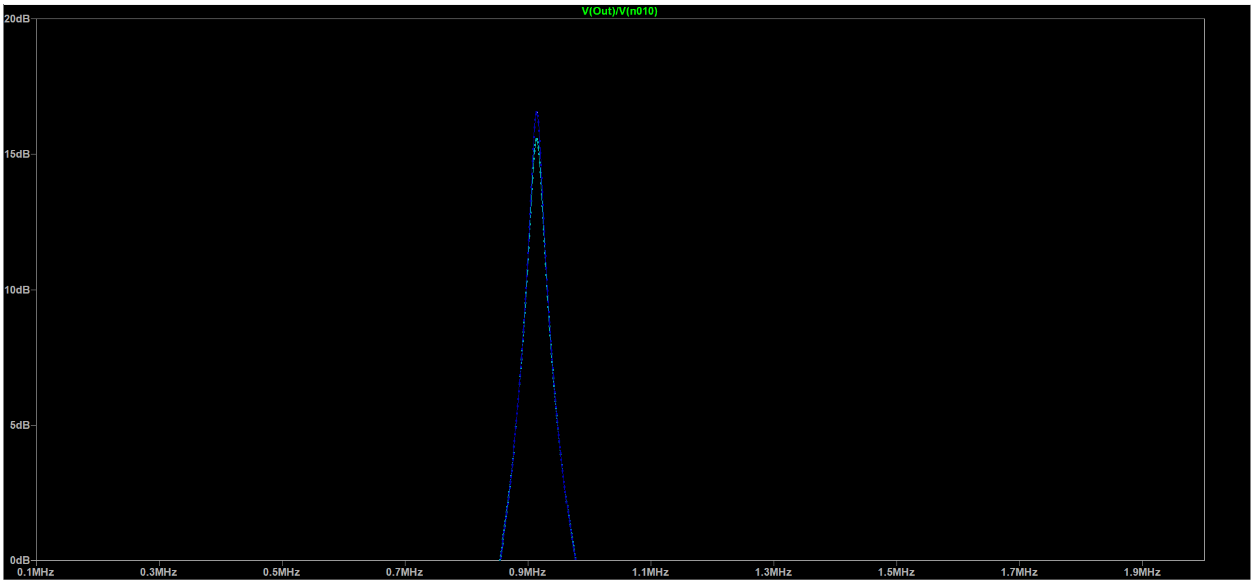

Fig.5-1-3 Tracking filter with updated feedback resistance centered at 0.9 MHz

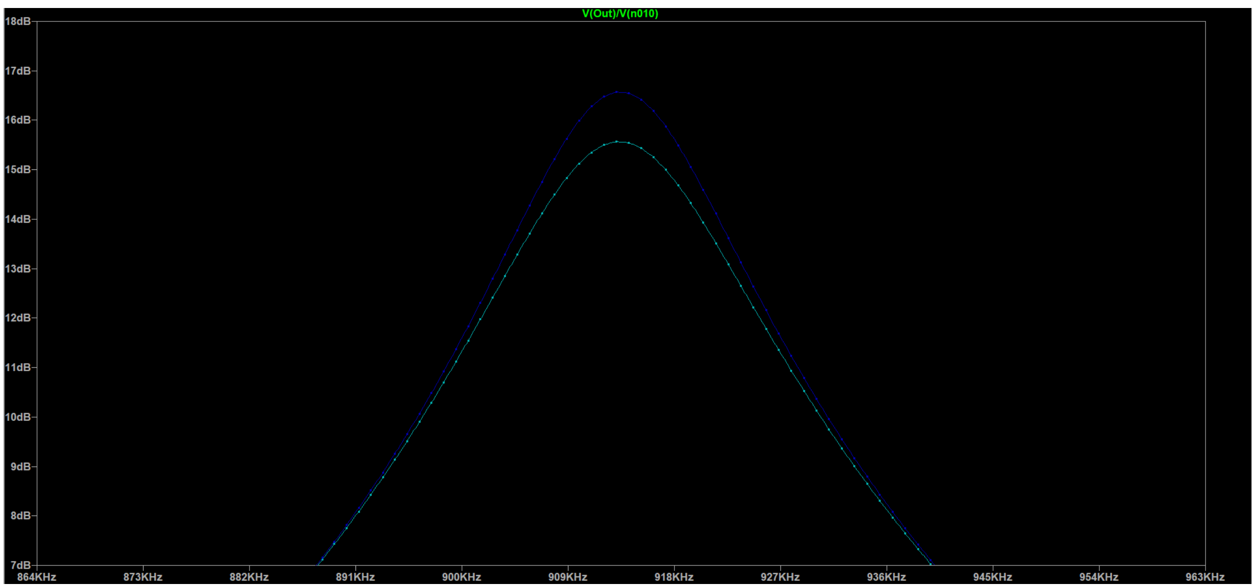

Fig.5-1-4 Tracking filter with updated feedback resistance centered at 0.9 MHz zoomed in

Prototype output of the tracking filter:

In order to validate the results of the simulation we built a breadboard prototype and connected it to a signal generator in order to test its response at different frequencies. We get a significantly better performance from the simulation with the prototype which when centered at approximately 912kHz in which we observe a 3dB decrease in power when the signal differs for 2kHz which means a 4kHz bandwidth. The fix for the stability problem on the real prototype gives us an opportunity for improvement by making the change in Q an easier parameter to manipulate.

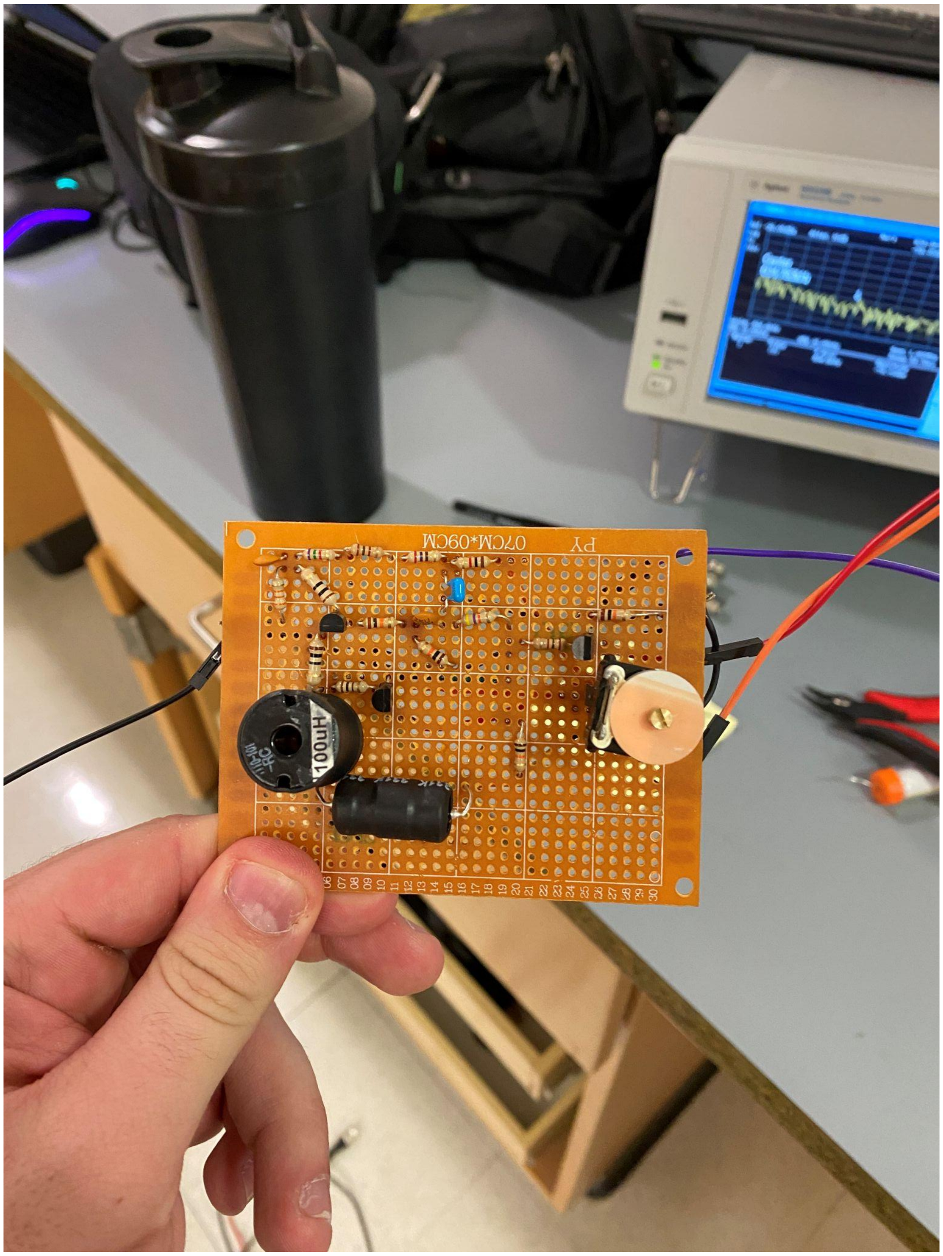

Fig.5-1-5 Tracking filter prototype

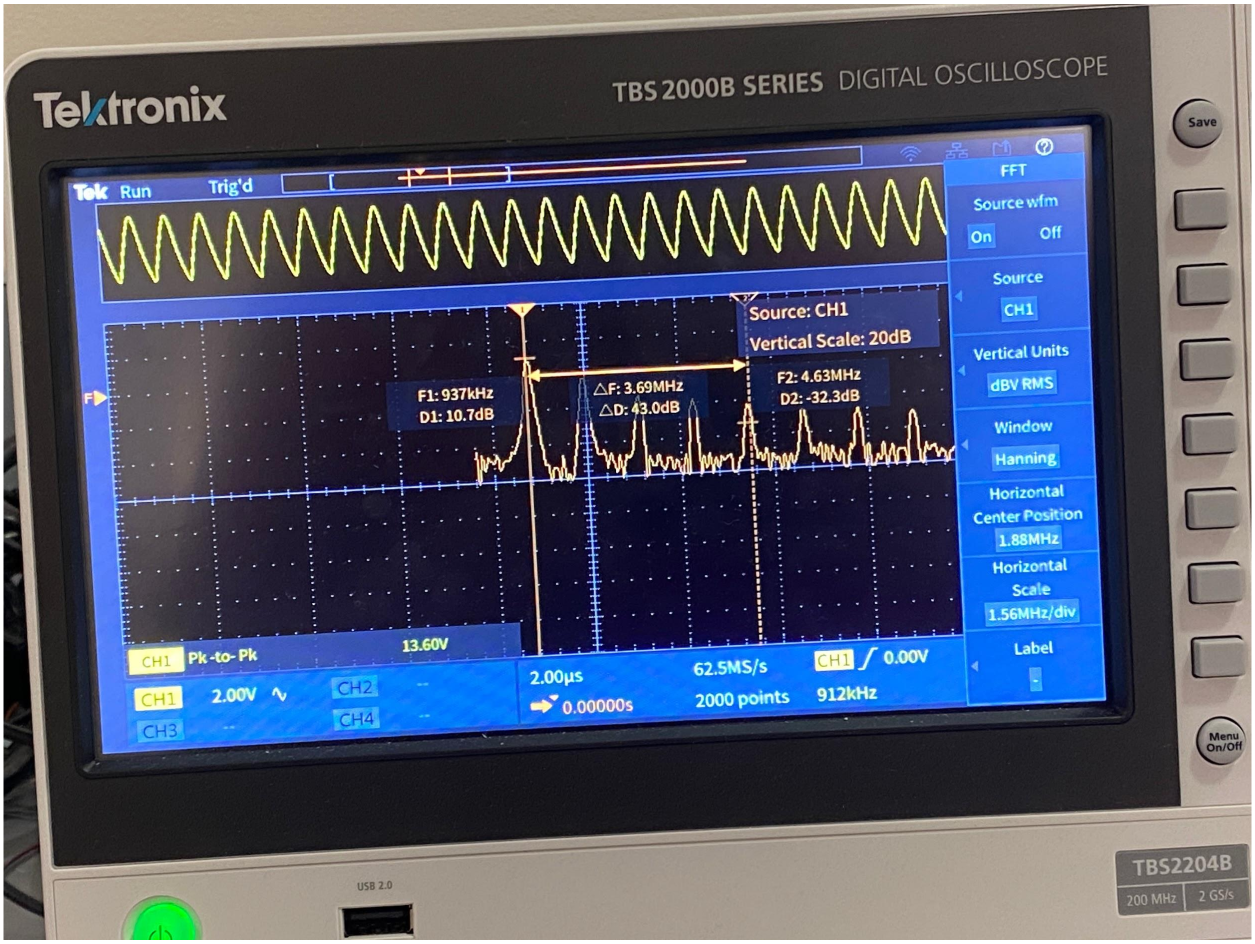

Fig. 5-1-6 Tracking filter prototype response at 912kHz ‘peak’ frequency

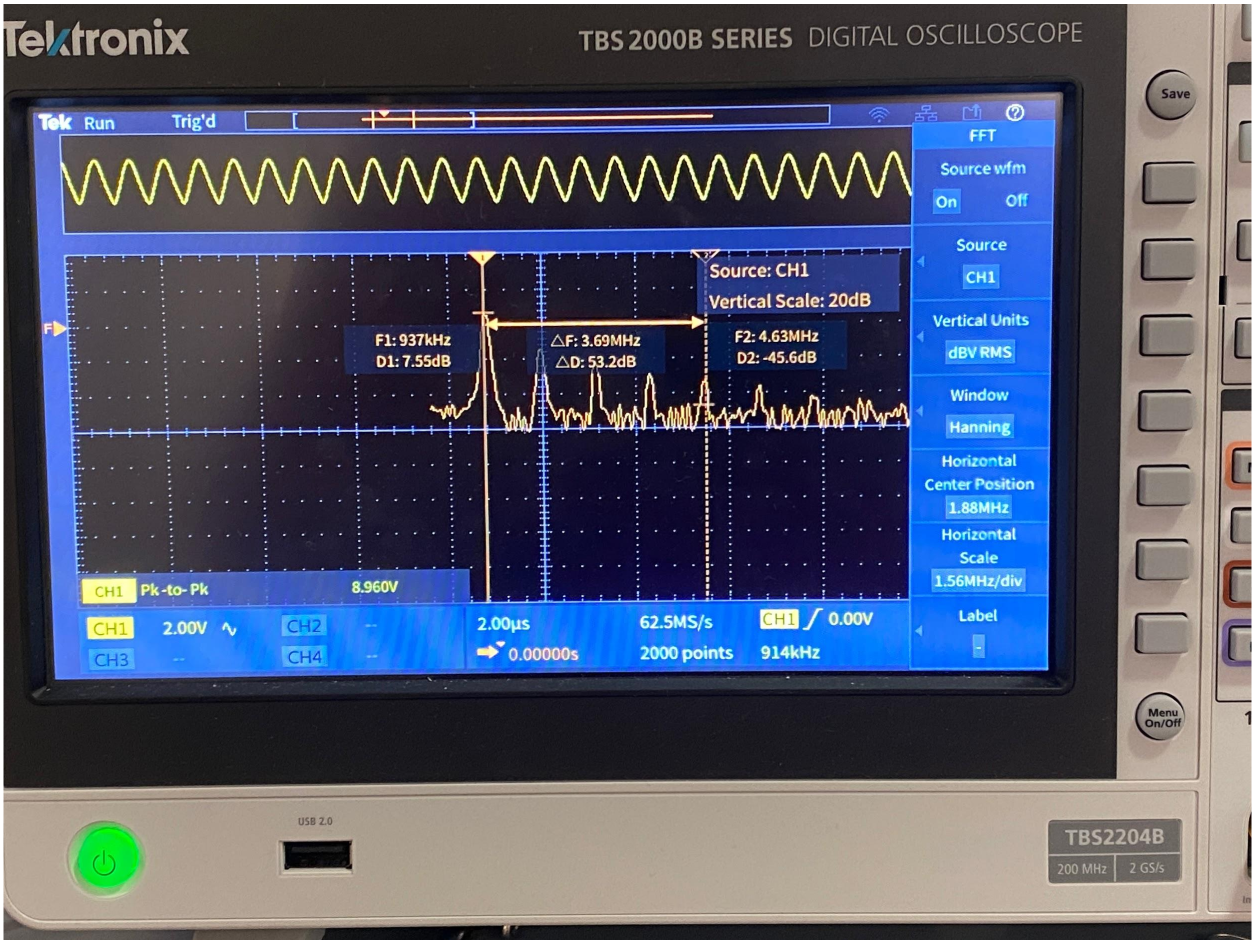

Fig.5-1-7 Tracking filter prototype response with a 914kHz input.

5.2 Improved version of the tracking filter:

Brief description of the improvement:

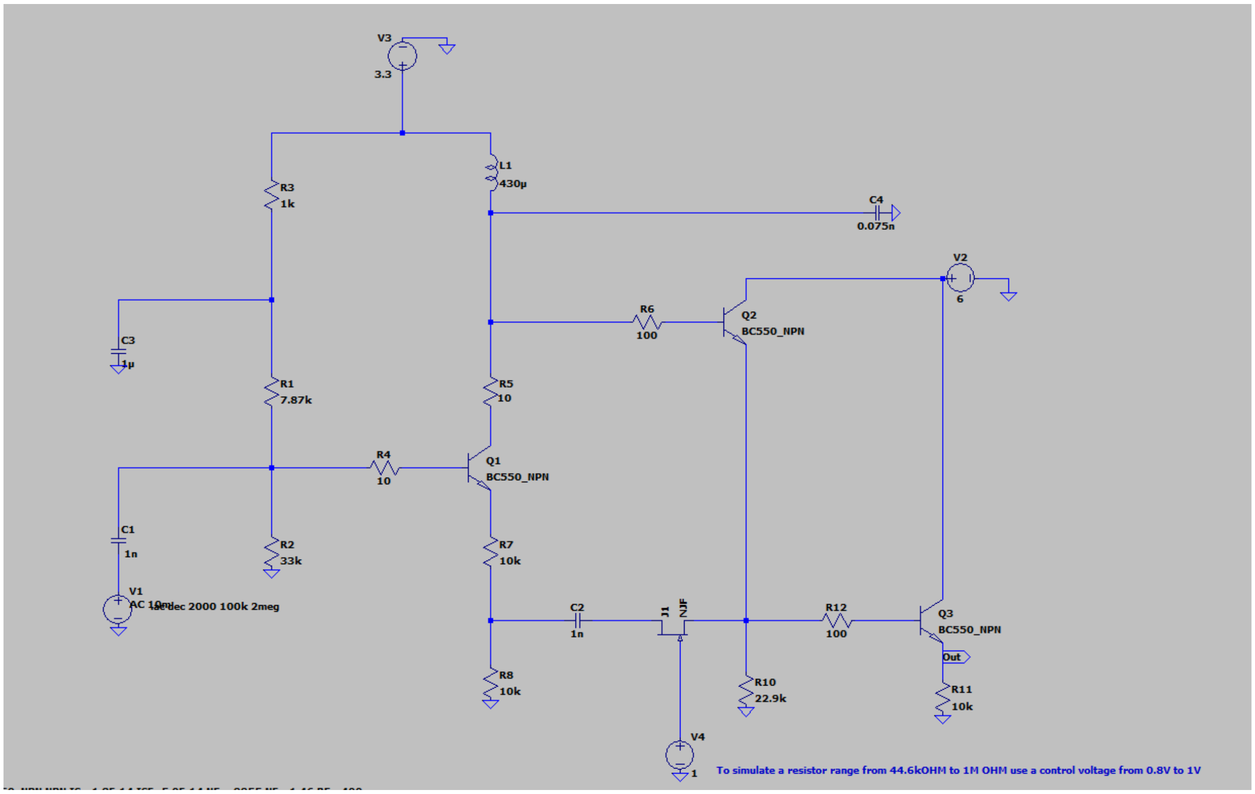

Fig.5-2-1 Improved Tracking Filter Mk1

In order to ease the change of the Q parameter by the end user we make use of the IV characteristics of JFETs. By setting the JFET into its ohmic region we achieve what essentially is a voltage controlled resistor. We achieve this 'biasing' current to sustain resistive behavior by changing the value of resistor R10. In order to control the resistance of the JFET we must add a control unit which will deliver a voltage control. For theory (and simulation) we could just deliver enough control voltage to turn on the JFET and thus create a filter with an almost ideal Q. If we do this and only deliver a 0.7V control we can obtain an amplification of 50dB with a bandwidth of 1kHz for a 1MHz target signal, greatly outperforming the original design.

A further improvement that simplifies the usage of the filter (although limiting the control of the end user upon its capabilities) is to set hard limits to the minimum and maximum feedback resistance in order to guarantee a more stable response of the filter. We achieve this by setting a minimum resistance in series with the JFET and a maximum resistance in parallel.

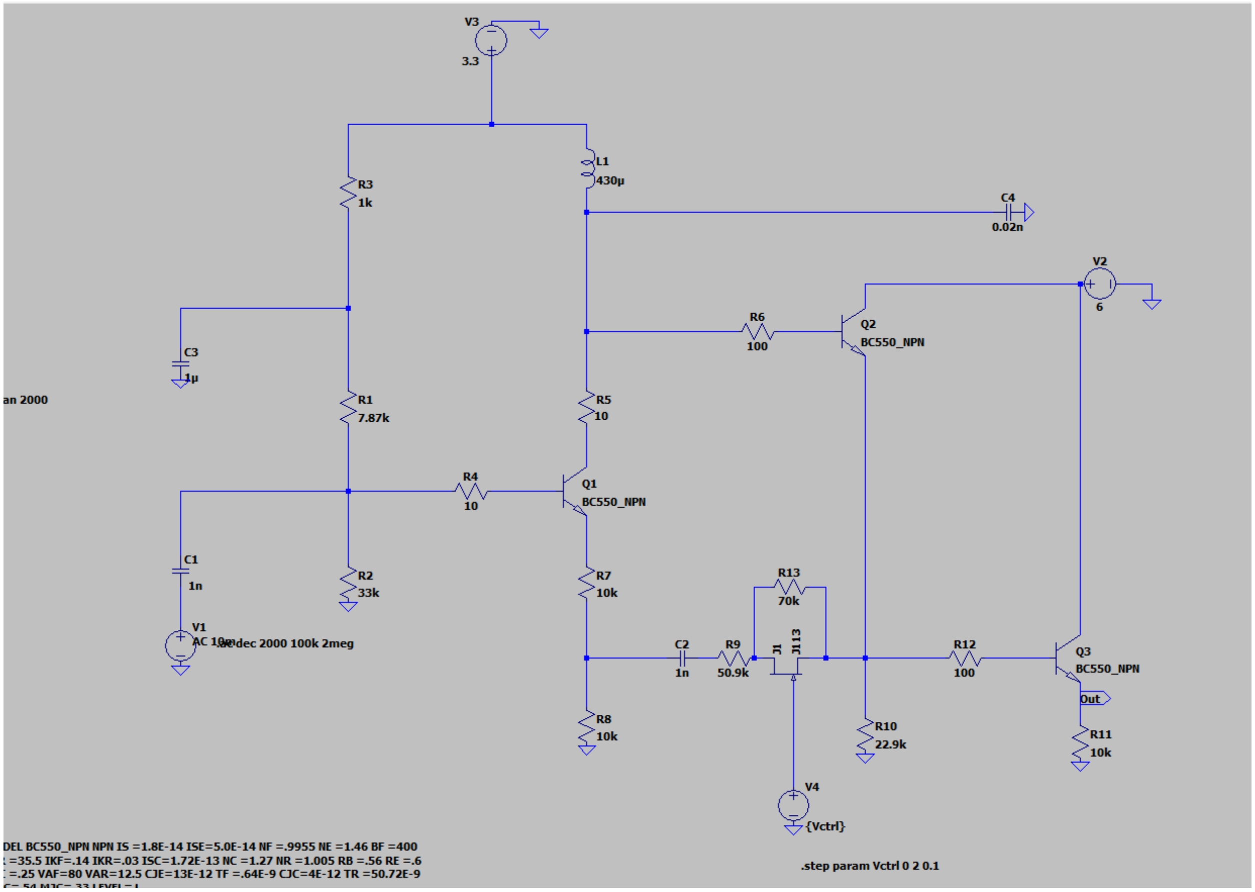

Fig.5-2-2 Improved tracking filter with hard limits

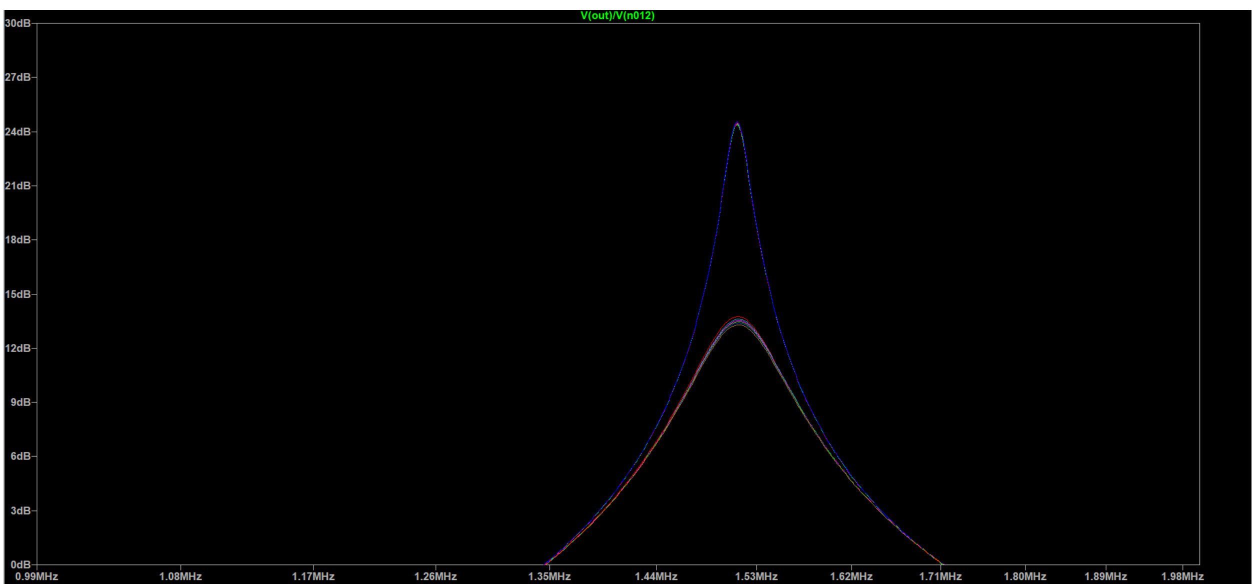

Fig.5-2-3 Hard limit tracking filter at different control voltages

Although the difference on gain at different control voltages might seem negligible once the JFET is 'turned on' it is important to remember that a change as small as 1 dB can make the difference between an oscillating filter and an isolated signal. Unfortunately given time constraints at the moment we're unable to verify these changes on the physical prototype.

5.3 Alternative improvements:

Our client advised us to use a MOSFET instead of a JFET for the Q control as to have an IV curve that the end user is more likely to be familiar with. The attempts at having this alternative transistor as the control for the filter's feedback were not successful, however this doesn't mean that the idea should be abandoned. If we had more time to work on the project this change would most likely be viable by changing the power distribution of the filter, taking special care of maintaining the ratio between R5 and R7, in such a way that the voltage at the source of the transistor is increased.

6 Triode Mixer

6.1 Original Version of the Trido Mixer

Brief description of the Triode Mixer:

The triode mixer is a key component of the AM radio localization system. The circuit uses a mixer to generate intermediate frequency (IF) signals by multiplying the radio frequency (RF) signal with a local oscillator (LO) signal. It takes inputs from the isolation amplifier (as RF), and a locally generated signal (as LO). For example, the mixer used in this circuit produces two new frequencies: RF-LO and RF+LO, which are separated by a constant 5 kHz offset. These new frequencies produce IF signals of 5kHz and another high frequency IF signal. The high frequency IF signal can be easily removed with a low-pass filter, leaving only the 5kHz IF signal. The mixer also keeps the phase, which makes it possible to measure the phase of high-frequency signals with great accuracy. The circuit diagram is post below:

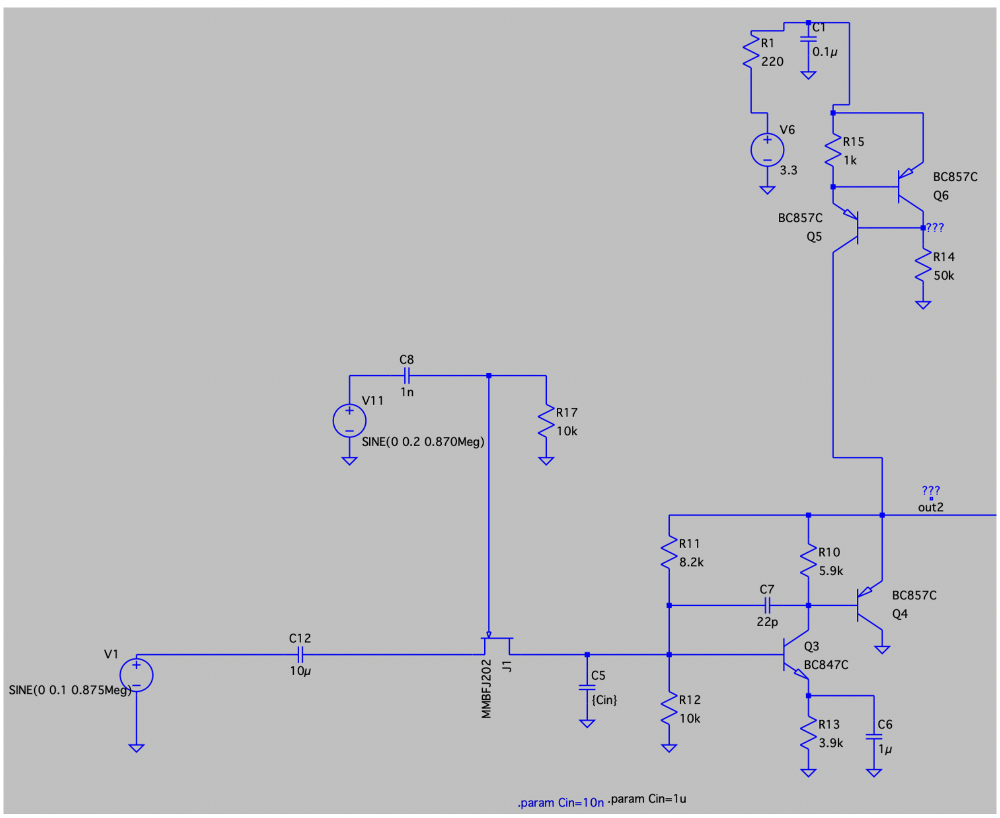

Fig.6-1-1 Original Triode Mixer Schematic

The V1 and V2 simulate RF and LO signals.

Simulation Outputs:

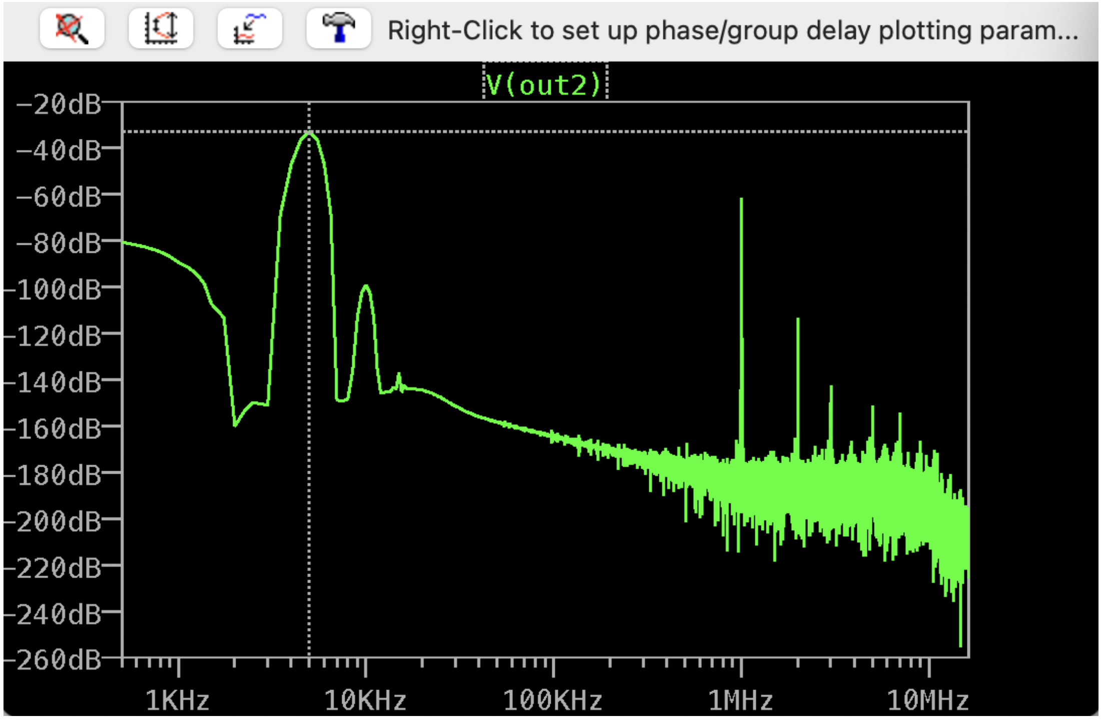

Fig. 6-1-2 Simulation Result in the Frequency Domain

A peak at 5 kHz with a magnitude of -33.4 dB can be observed in Figure 5-1-2.

Testing Outputs:

For the breadboard validation of the triode mixer circuit, the experiment setting and output are stated below. Two function generators that simulate RF and LO signals are responsible for producing the inputs. The first function generator generates a sine wave with 1.005 MHz frequency, 0.1 V amplitude, and no offset voltage. The other outputs a sine wave with a 1 MHz frequency and the same amplitude and offset. The output measured by an oscilloscope shows a 5 kHz wave in time domain, and an amplitude peak at 5 kHz after FFT.

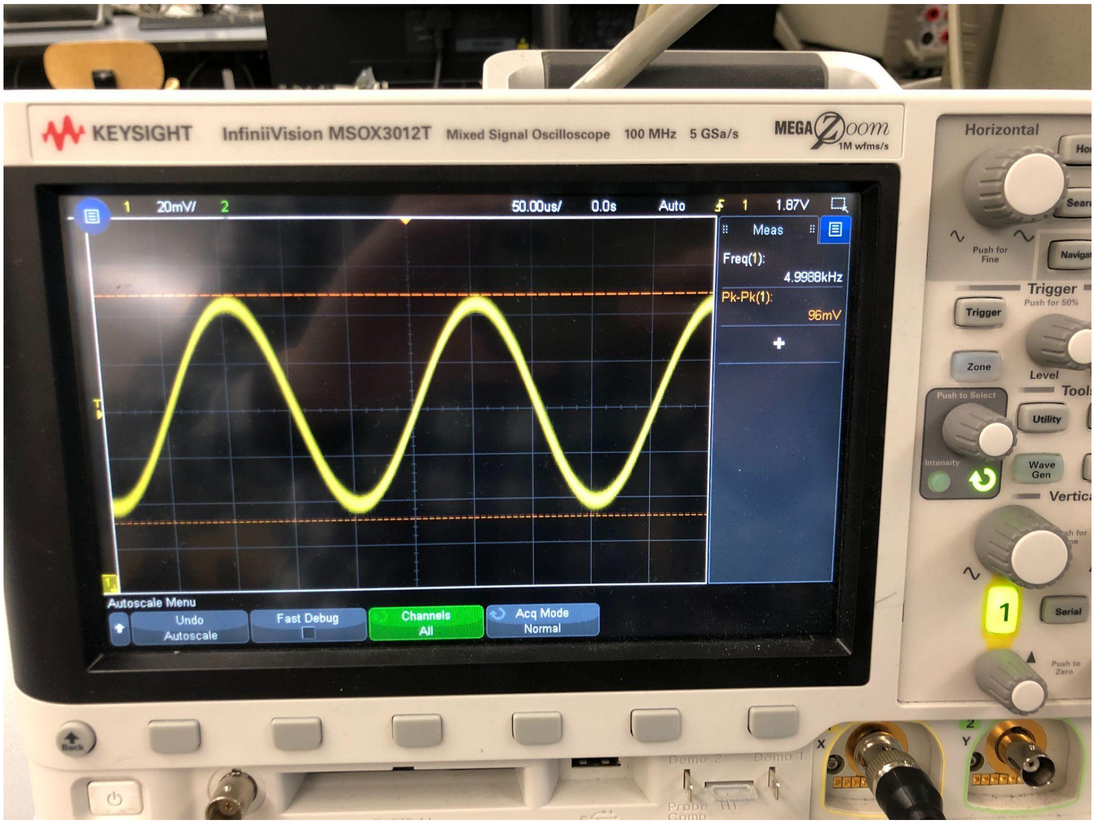

Fig. 6-1-3 Test Output of the Original Triode Mixer

6.2 Improved Version of the Triode Mixer

Brief description of the improved version:

The improved version of the triode mixer circuit is posted below. The main improvement is in the conversion gain of this mixer, which is a measure of how much the output signal amplitude is increased or decreased relative to the inputs. We mainly focus on two factors: the first is to increase the power of the input signal from the local oscillator with an emitter follower and set the most suitable bias current with the Rb resistor. The second is to improve the conversion gain by optimizing the gate-drain bias voltage of JFET J1. The DC voltage source, BiasVol, controls the bias voltage. In the improved triode mixer, R3 is reduced to 40 Ohm to obtain the largest power input from VCO, and BiasVol is set at -0.95 V to increase the gate-drain bias voltage to around -1.9 V. The improved output has a 0.025 V larger amplitude shown in time domain simulation, which is around 40% improvement of its original output. After FFT, at the desired 5 kHz frequency output, the improved version is around 2dB larger than the original one. As shown in figure 6-2-2 and 6-2-3, the original output is in blue, and the improved one is in green.

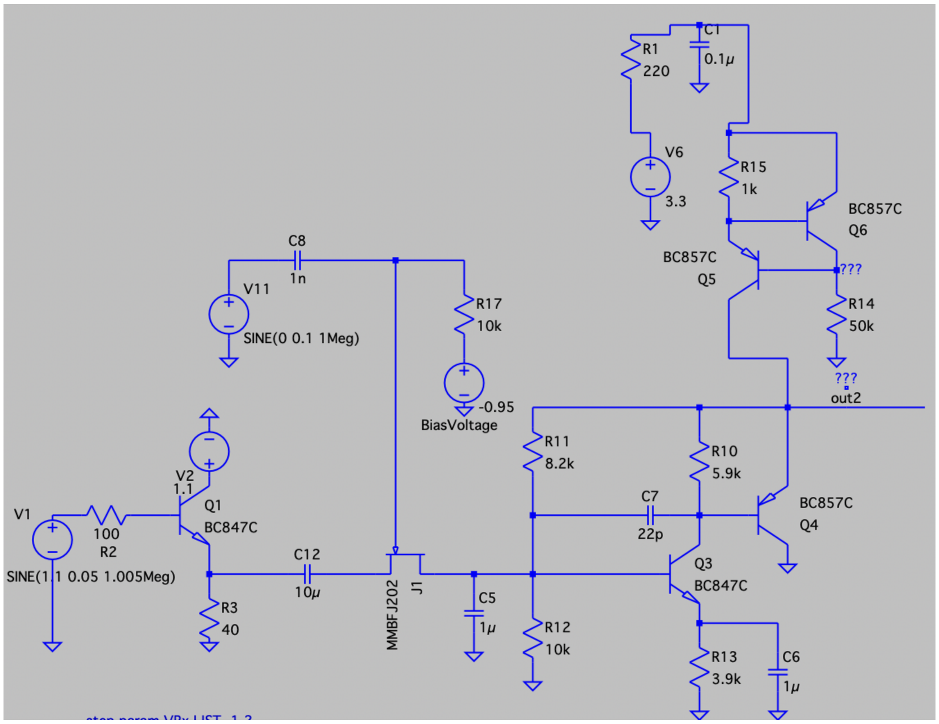

Fig.6-2-1 Improved Triode Mixer Schematic

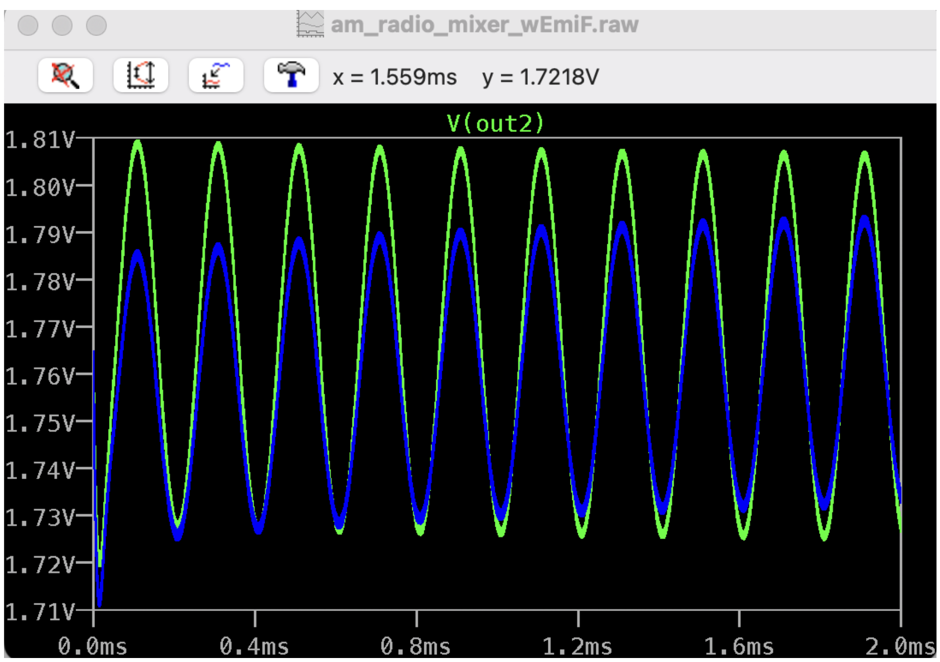

Fig.6-2-2 Improved Triode Mixer Simulation Output

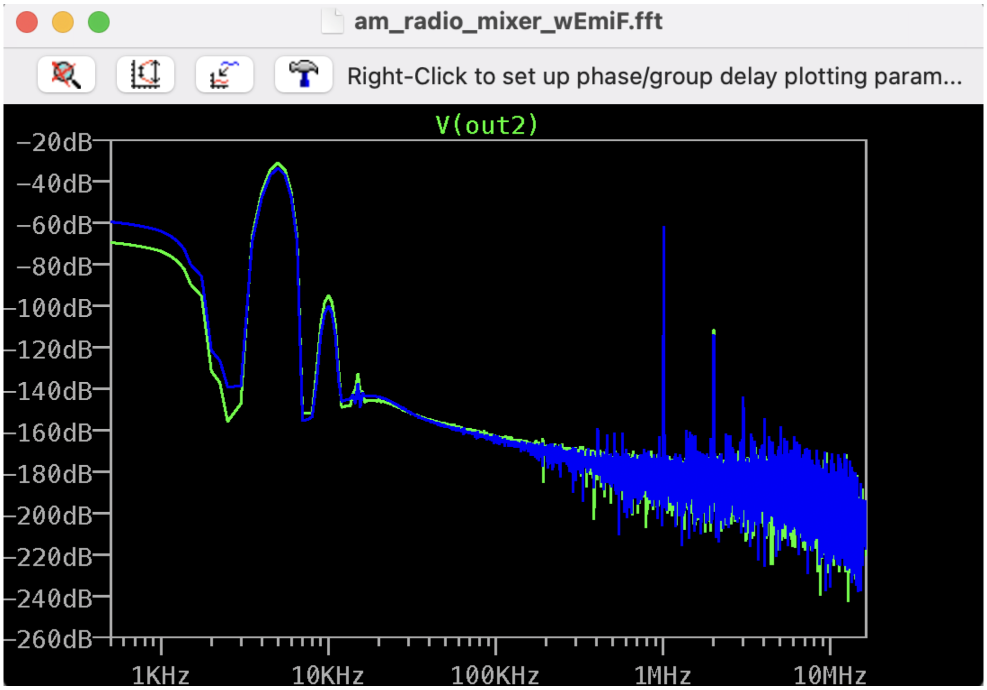

Fig.6-2-3 Simulation Output after FFT

R3 (Ohm)	Output after FFT(dB)		BiasVol(V) R3=40		Output after FFT(dB)
150 (Original)	-33.47		-0.5		-31.86
140	-33.4		-0.8		-31.22
100	-33.16		-0.95		-30.89
50	-32.91				
40	-32.89				
30	-32.91				
10	-33.48				
5	-34.57				

Fig.6-2-4 Output Value for Different R3 and BiasVol value

7 Combined Circuits(Active Antenna, INA, Tracking Filter, and Triode Mixer)

Final Prototyped Version

Brief description of the combined system:

This prototype consists of four circuits (Active Antenna, INA, Tracking Filter, and Triode Mixer), the schematic and the prototype are shown in *Fig.7-2-1 & Fig.7-2-2*. Its goal is to test or identify one of the AM radio signals by setting the LO mixer input to 860 KHz, tuning the tracking filter to one of the AM radio frequencies (850 KHz in this experiment), and expecting to get a 10 KHz IF output from the mixer. At the conclusion of this prototype's testing, the detection of the AM radio signal was successful.

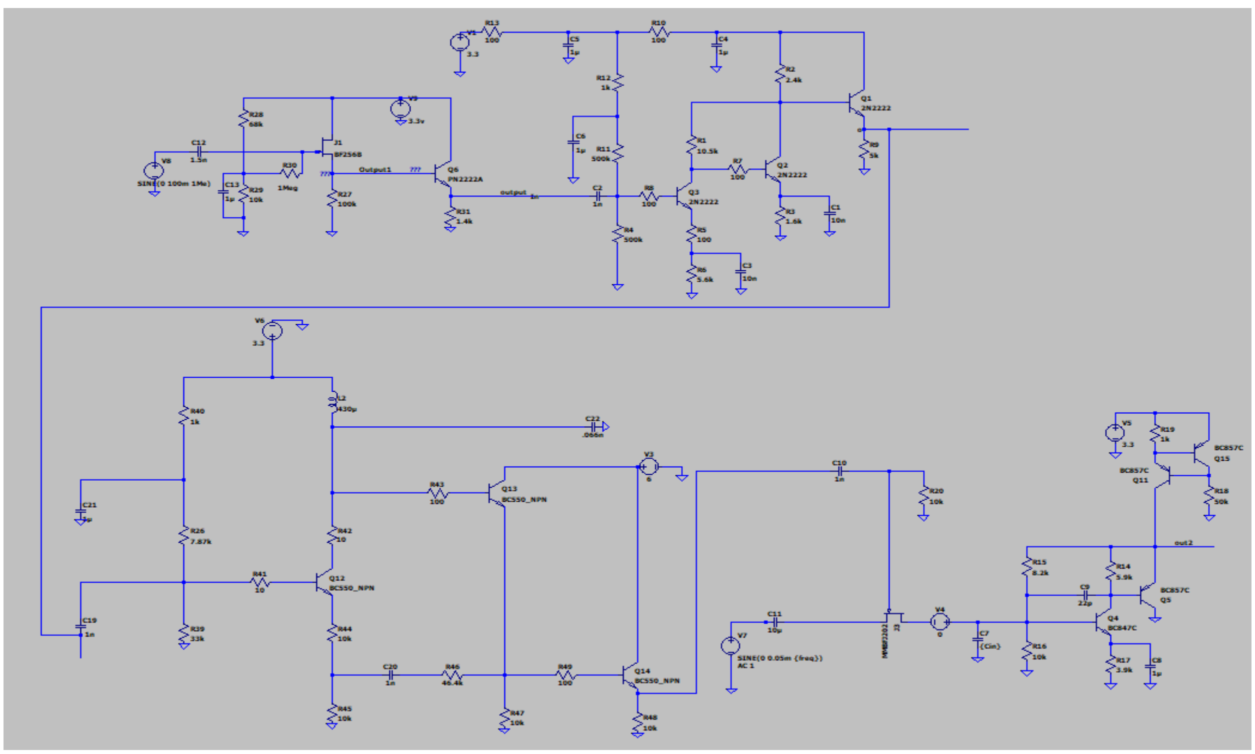

Fig.7-2-1 Overview of the system schematic

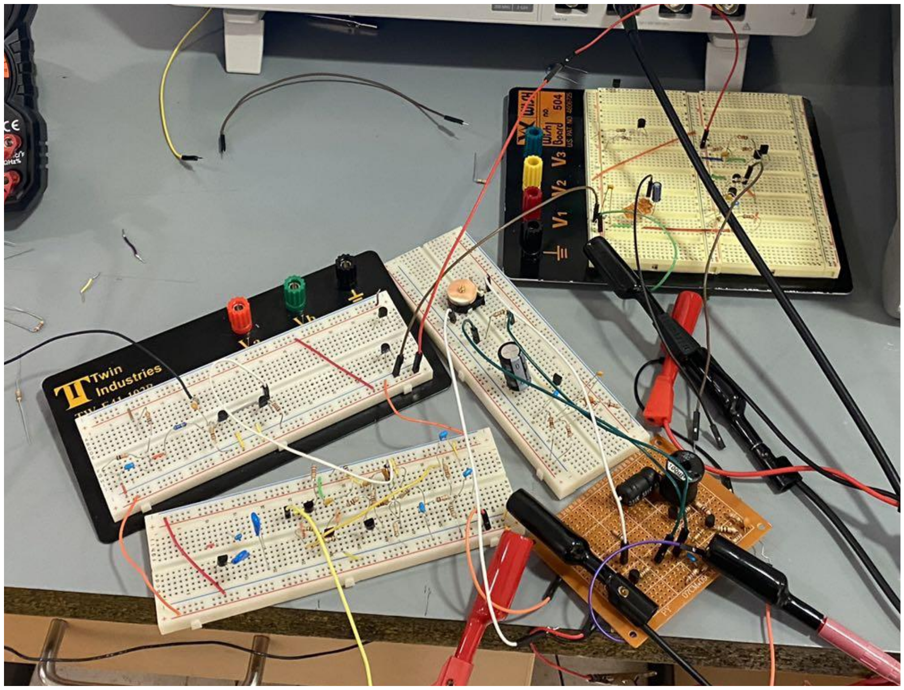

Fig.7-2-2 Project Hardware (Active Antenna, Isolation Amplifier, Tracking Filter, and Triode Mixer)

Equipment and Setup:

We combined and tested the four circuits we made. The circuits that are being tested are Active Antenna, Isolation Amplifier, Tracking Filter, and Triode Mixer. The schematic of the combined system is in Fig.. The required hardware is a function generator, power supply, and oscilloscope. First, we powered up the active antenna and hook it with up to 10 ft 28 gauge wire to the input of the active antenna, then connect 3.3V DC voltage to power up the antenna. The isolation amplifier's input will then be connected to the output of the active antenna and powered up by a 3.3V DC power supply, the isolation amplifier should be able to amplify the input signals by a factor of 15. Then the input of the tracking filter will be connected to the output of the isolation amplifier, and the output of the tracking filter will serve as an input for the triode mixer.

Simulation Result:

1. Tracking Filter FFT: variable capacitor = 0.071n (Sets RF = 850KHz)

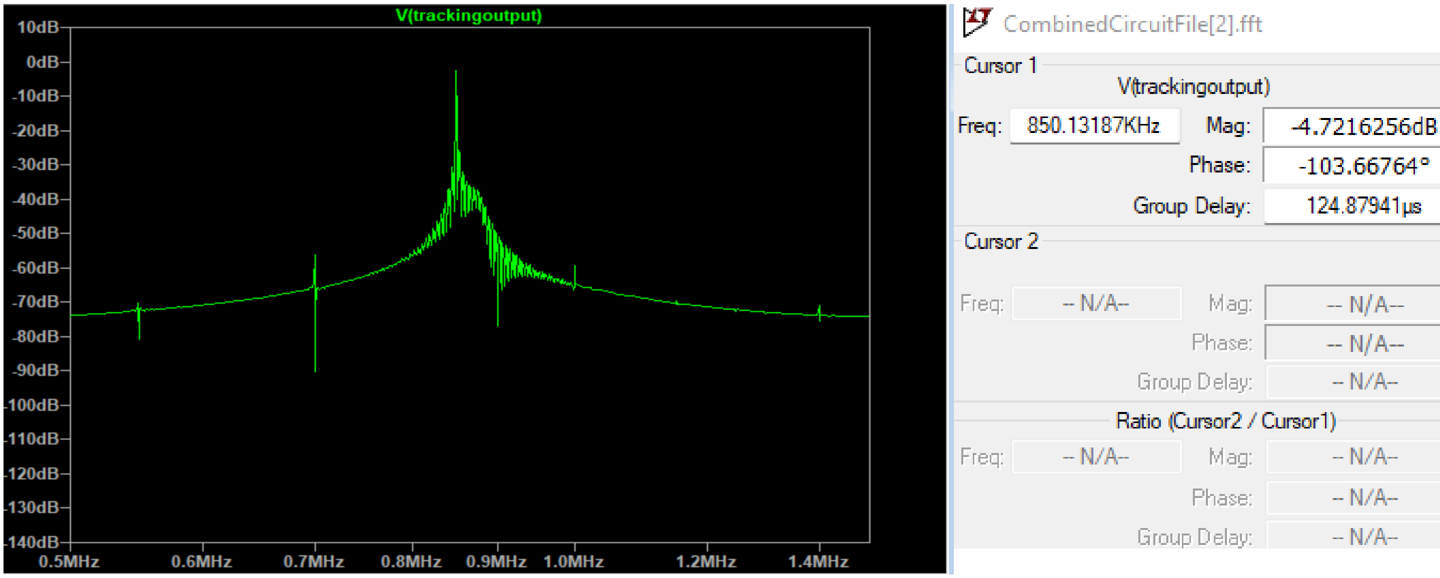

Fig.7-2-3 FFT of Tracking Filter output

2. Triode Mixer FFT: Input of 860KHz from a function generator (LF = 860KHz)

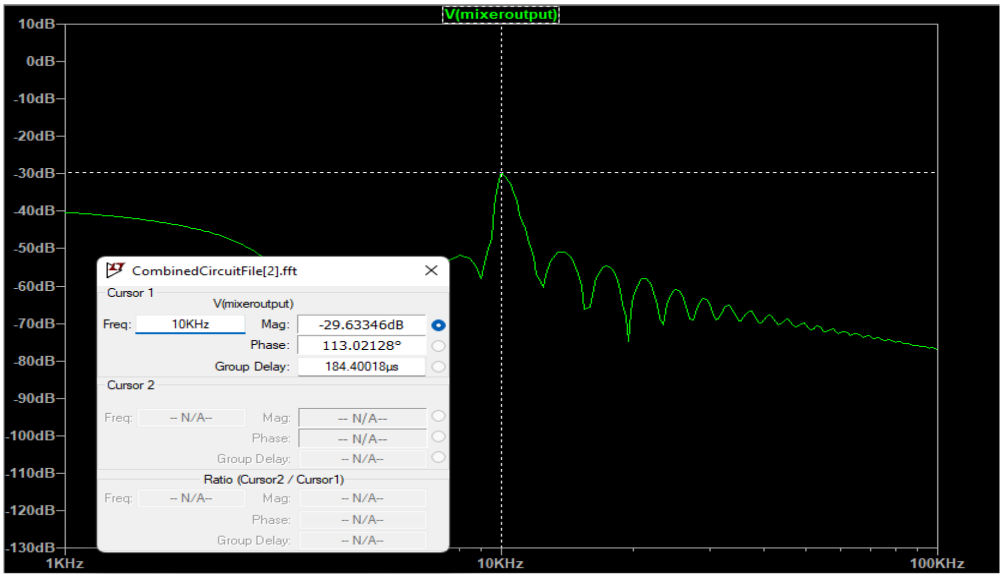

Fig.7-2-4 FFT of Triode Mixer output

The simulation gives an accurate intermediate frequency output given by the table in *Fig.7-2-4*. of

10KHz, in which the intermediate frequency response is calculated by the local oscillator frequency of 860KHz (input from the function generator) minus the radio frequency of 850 KHz.

Test Output/Measurements:

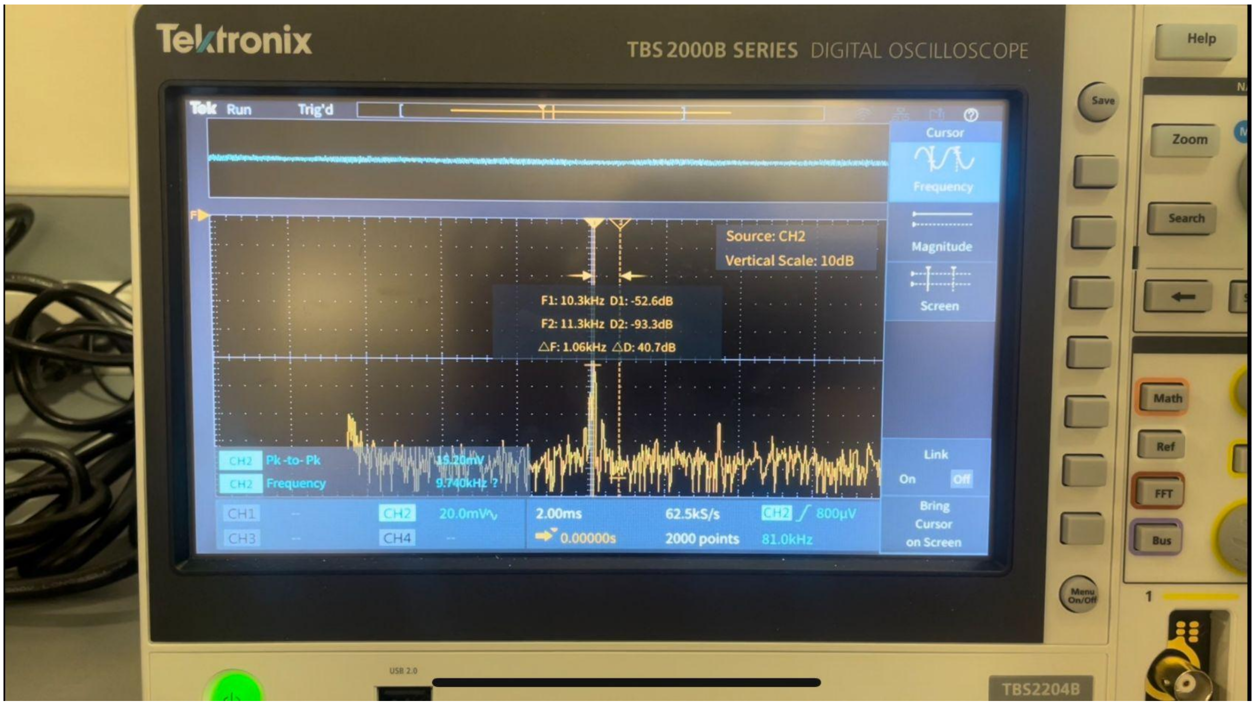

Fig.7-2-5 FFT of Triode Mixer Oscilloscope Output

Conclusion:

From *Fig.7-2-5*, we can see that there is a peak at 10.3kHz which is what we expected. The result (10.3kHz) is the relative close as the simulation results (10kHz) with a difference of 0.3kHz and a percentage error of 3%. Since 3% is much less than 10%, we conclude that the combined circuit works properly and has met all the requirements.