Ultrasonic Radio

Nathan Cinocca

CONCEPT OF OPERATIONS

REVISION – Draft
25 January 2018

CONCEPT OF OPERATIONS
FOR
Ultrasonic Radio

TEAM 84

APPROVED BY:

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Project Leader Date

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Prof. Kalafatis Date

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T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	9/14/2023	Nathan Cinocca		Draft Release

Table of Contents

List of Tables

List of Figures

1. Executive Summary

Communicating information is an important aspect of almost any military operation. However, depending on the situation, it can be difficult to transmit information safely. For example, in planes and submarines it is difficult to communicate with regular equipment as the electromagnetic waves will interfere with the vehicles navigating equipment. To solve this issue, an ultrasonic radio will be developed that will operate at a low frequency using acoustic waves outside of the range of human hearing. The radio will also have multiple channels that will allow for two-way communications between correspondents. Ultimately, this radio will allow for better communication between military operators even around areas that are sensitive to electromagnetic waves.

2. Introduction

This report is an introduction to the development of an ultrasonic radio. This ultrasonic radio will be designed to operate using low frequency acoustic waves outside of the range of human hearing to transmit data without affecting other electromagnetic waves at higher frequencies. This ultrasonic radio will primarily be used for military operations that involve planes, submarines, and other forms of transportation with sensitive equipment. However, this radio could also be used by civilians in similar situations.

2.1. Background

Radios have been around for a very long time and operate at a large range of frequencies from 3 Hz to 300 GHz. However, most of these radios use electromagnetic waves to transmit information. Radios that use electromagnetic waves are effective methods of communication as they can send and receive information very quickly. Despite this electromagnetic wave-based communication can have problems where multiple devices create wave interference. This can be a very dangerous issue when sensitive, vital equipment such as airplane equipment is interfered with. The danger of electromagnetic wave interference is multiplied in dangerous military situations.

A way to get around the limitations posed by electromagnetic waves and their applications is to create an ultrasonic radio that uses acoustic waves. Using acoustic waves at lower frequencies will allow for minimal electromagnetic interference but will limit range of transmission. This trade off is acceptable as it will allow for safe communication during military operations in both planes and submarines.

In my research I have only found one ultrasonic acoustic radio that has been developed. This radio was developed by Qin Zhou, Jinglin Zhenga, Seita Onishia, M. F. Crommie, and Alex K. Zettl. Their ultrasonic radio is designed to operate at a band centered around 300 kHz with only a single channel. Their design is effective, but I plan to improve upon it by lowering the operational frequency to have less interference. I also plan to add multiple channels to allow for two-way communication.

2.2. Overview

There are many different parts involved in creating this ultrasonic radio and a large focus for this project will be designing individual parts. An overview of the components involved in this radio is as follows. Firstly, the incoming signal will be amplified using a transistor-based amplifier. Then the signal will be filtered using a bandpass circuit and moved to a higher frequency, if necessary, with a mixer. Next, the signal will be modulated using frequency modulation. Then the signal will be filtered once more for noise and amplified with a power amplifier of very large gain (~100 dB). After this the signal will pass through the input transducer and the output transducer. After the signal passes through the output transducer the signal will be amplified again using a transistor-based amplifier, and then filtered. Finally, the signal may be filtered again to reduce noise before the final signal is output.

2.3. Referenced Documents and Standards

- Graphene electrostatic microphone and ultrasonic radio (pnas.org)
- *C95.1*, Standard for Safety Levels with Respect to Human Exposure to Radio-Frequency Electromagnetic Fields, 3 kHz to 300 GHz

3. Operating Concept

3.1. Scope

The ultrasonic radio is primarily intended to be used for military operations in areas where electromagnetic communications are difficult. This primarily includes during plane and submarine transportation. The ultrasonic radio could also be used at a lower capacity by regular consumers during flights.

3.2. Operational Description and Constraints

The ultrasonic radio should be simple to operate and will be operable without any in-depth knowledge or training. Essentially you should be able to speak on one side of the radio and hear the output of your voice on the other side in relative clarity. The radio will also allow you to both speak and listen to noise at the same time. This will be accomplished through two frequency channels.

There are several constraints that come with this project. One of them is the cost constraint. As a capstone student, I am afforded $100 to spend on our project. Since I will need to purchase transducers at an absolute minimum which can be relatively expensive. Because of this I will most likely be using discrete components to design the amplifiers and filters. This will lead to more noise and less precision in the designs. Another constraint on this ultrasonic radio is that since the system will be using acoustic waves, the transmission of information will be slower than most electromagnetic wave transmissions.

3.3. System Description

The ultrasonic radio can be divided into roughly five different parts. These include signal amplifiers, filters, signal modulator/demodulator, power amplifier, and the input/output transducers.

The signal amplifier will be used to amplify the noise input and output from the radio. The signal amplifier will be designed from discrete transistors. I will attempt to keep the power consumption relatively low by limiting the voltage <10 V and current to <15mA.

The filters will primarily be used to get rid of noise. I will use an IC operational amplifier for this application instead of designing the amplifier from scratch. For the filters used for both the input and output signal I will need them to operate at two different frequencies to accommodate the different channel frequencies. These frequencies will be in the 50k Hz to 100k Hz range.

Next, I will need to design a frequency modulator and demodulator. To do this I will need an oscillator and some IC op amps. This will also include many resistors and capacitors to operate properly.

I will also design a power amplifier with transistors. This amplifier will need to have a very large gain of around 100 dBs. This will be important to allow the signal to be transmitted a large distance.

Finally, I will need to purchase transducers that will function with the rest of the circuit. They will also need to function within the channel frequencies of 50k Hz – 100kHz.

3.4. Modes of Operations

Many radios are only half-duplex and only allow for one party to speak at a time. With this set up, a button is typically needed to activate the transmission from one radio to the other. However, since this ultrasonic radio will be full-duplex and allow for both parties to speak at the same time, there will be no need for this mode.

Instead, ultrasonic will simply have two modes. The first being the on mode, or the mode that will allow signal transmission. The other mode will be the off mode where no power will be consumed, and no signal will transmit.

3.5. Users

The ultrasonic radio is primarily intended to be used by military personnel usually during plane and submarine transportation. The ultrasonic radio could also be used at a lower capacity by regular consumers during flights. The radio should be able to be used with very little experience and a short manual. Overall, the radio should be usable by both the military and civilians with relative ease.

3.6. Support

The ultrasonic radio will be intuitive to use and as such should be usable without many instructions. However, a short manual would be provided with some instructions should it be needed.

4. Scenario(s)

4.1. Plane Communications

The first scenario in which the ultrasonic radio could be used is in the case of plane transportations. To avoid the impact of electromagnetic waves the ultrasonic radio could be used by both military personnel and civilians traveling in planes. This would allow communication between individuals on and off the plane.

4.2. Submarine Communications

Similar to the first scenario the ultrasonic radio could be used to avoid electromagnetic wave interference with submarine instruments. This scenario is less applicable to the public as few civilians use submarines for transportation. The radio would allow contact between submarines or contact between submarines and individuals on land depending on the distance.

5. Analysis

5.1. Summary of Proposed Improvements

- Allows for safer communication around equipment sensitive to electromagnetic waves
- Improves upon old design to allow both parties to speak and listen simultaneously
- Communication system is easy to use

5.2. Disadvantages and Limitations

- The ultrasonic radio with acoustic waves will have less range than an electromagnetic radio
- Increased noise due to cheaper components from budget limitations
- Slower transfer of information due the low operational frequency

5.3. Alternatives

- Improved electromagnetic shielding
  - Shield sensitive plane/submarine components from all other EM waves so that regular electromagnetic communications can be used
  - Could be more effective but would be much more expensive and technically difficult

5.4. Impact

- The ultrasonic radio must abide by radio frequency standards
- The radio may be used to gain a tactical advantage in military operations

Ultrasonic Radio

Nathan Cinocca

FUNCTIONAL SYSTEM REQUIREMENTS

REVISION – Draft
28 September 2023

Functional System Requirements
for
Ultrasonic Radio

Prepared by:

Team 84

Approved by:

Nathan Cinocca Date

John Lusher, P.E. Date

T/A Date

Change Record

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-	9/28/2023	Nathan Cinocca		Draft Release

Table of Contents

List of Tables

List of Figures

6. Introduction

6.1. Purpose and Scope

This document covers the functional system requirements for the project. The purpose of the project is to provide an alternative way to send communications that does not use electromagnetic waves. By limiting the creation of electromagnetic radiation, this ultrasonic radio will allow for communications in locations that are susceptible to electromagnetic interference. To do this, the radio will operate at lower ultrasonic frequencies as opposed to higher electromagnetic wave frequencies. Additionally, acoustic waves will be used instead of electromagnetic waves.

This specification defines the technical requirements for the development items and support subsystems delivered to the client for the project. Figure 1 shows a representative integration of the project in the proposed CONOPS. The verification requirements for the project are contained in a separate Verification and Validation Plan.

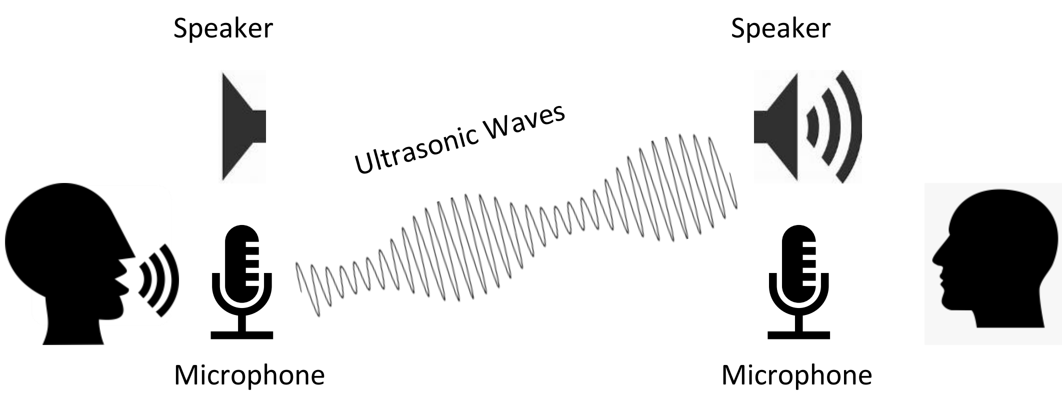

Figure 1. Ultrasonic Radio Conceptual Image

The following definitions differentiate between requirements and other statements.

Shall:	This is the only verb used for the binding requirements.
Should/May:	These verbs are used for stating non-mandatory goals.
Will:	This verb is used for stating facts or declaration of purpose.

6.2. Responsibility and Change Authority

The sole team member, Nathan Cinocca, will be responsible for verifying the requirements of the project are achieved. Any changes to the project may only be enacted through an agreement between Nathan Cinocca and the sponsor Dr. Oscar Moreira. Subsystem ownership for this project is listed below.

- Nathan Cinocca: Signal Amplifier, Filters, Modulator/Demodulator, and Power Amplifier

7. Applicable and Reference Documents

7.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	Revision/Release Date	Document Title
IPC A-610E	Revision E – 4/1/2010	Acceptability of Electronic Assemblies
MIL-STD-461	Revision E – 8/20/1999	Requirements for the Control of Electromagnetic Interface Characteristics of Subsystems and Equipment
IEEE Standard C95.1	4/16/1999	Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz

Table 1. Applicable Documents

7.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Number	Revision/Release Date	Document Title
1	2015	Graphene electrostatic microphone and ultrasonic radio
2	2010	Analog and Digital Communications
3	2011	RF and Microwave Transmitter design
4	2014	FM Modulation/de-modulation circuit
5	2009	Engineering Acoustics: An Introduction to Noise Control
5	2020	Thermal Stress Inside a Disabled Submarine

Table 2. Reference Documents

7.3. Order of Precedence

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence without any exceptions.

All specifications, standards, exhibits, drawings or other documents that are invoked as “applicable” in this specification are incorporated as cited. All documents that are referred to within an applicable report are considered to be for guidance and information only, except ICDs that have their relevant documents considered to be incorporated as cited.

8. Requirements

This section defines the minimum requirements that the development item(s) must meet. The requirements and constraints that apply to performance, design, interoperability, reliability, etc., of the system, are covered.

8.1. System Definition

Provide a brief overview of the project, and then describe some of the main sub-systems of your proposed solution.

The ultrasonic radio is a method of communication that limits the creation of electromagnetic waves so electromagnetic interference is minimized. By minimizing the emission of electromagnetic waves, this communication device will allow for information transfer around devices sensitive to other electromagnetic waves. This ultrasonic radio will limit electromagnetic wave emission by using acoustic waves and low ultrasonic frequencies to transmit information. The ultrasonic radio is largely made up of five different subsystems. These subsystems include: the signal amplifier, filters, power amplifier, modulator/ demodulator, and the speakers/microphones.

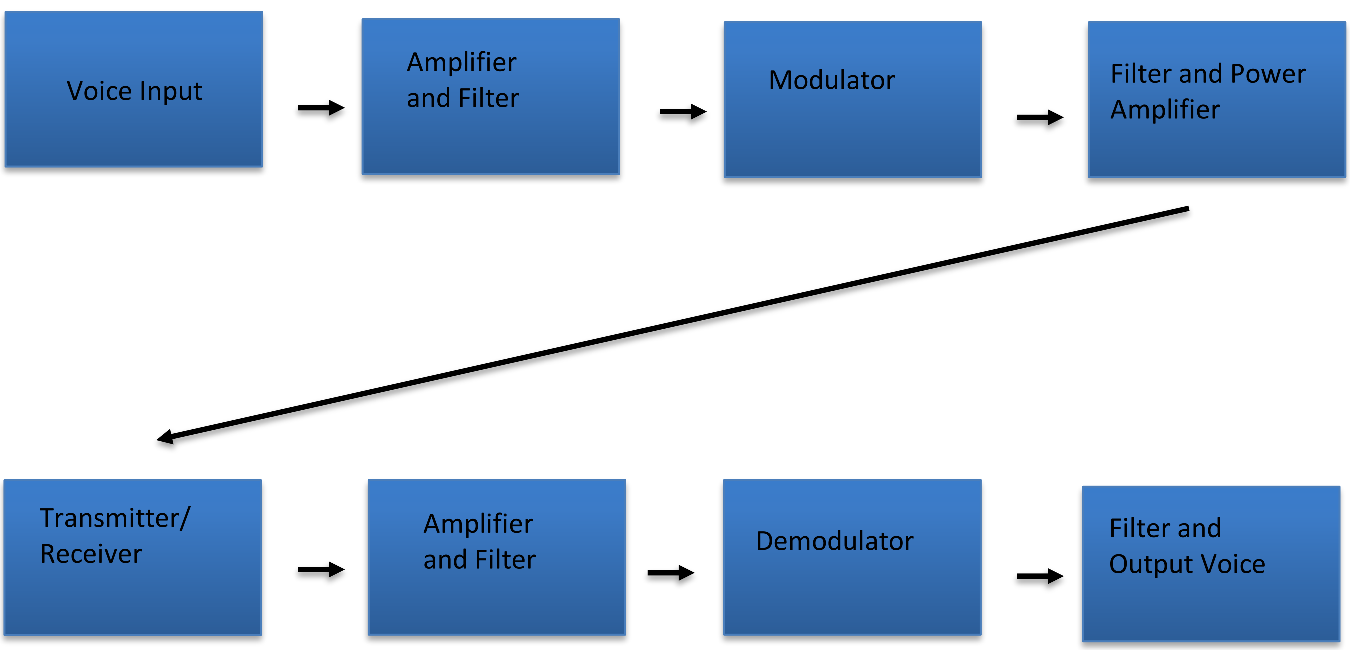

Figure 2. Block Diagram of System

The first part of the ultrasonic radio is the input microphone which will operate to encompass human voice frequencies. This range of operational frequencies will be around 100 Hz to 3 kHz. This microphone will translate the voice into an electrical signal that will then be amplified and filtered through the signal amplifier and low frequency filter. This will make the signal stronger and filter out unneeded noise being picked up by the microphone. Following this, the signal will go through a modulating circuit which moves the input signal to ultrasonic frequencies to prepare for transmission. After modulation, the signal may be filtered if additional noise is picked up at the higher ultrasonic frequency. Then the modulated signal will go through the power amplifier which will give the signal the desired gain to transmit through the ultrasonic speaker to the ultrasonic microphone some distance away. Once the signal is picked up by the microphone it will be filtered and amplified again to prepare for demodulation. Then the signal will be demodulated down to frequencies within the range of human hearing. Finally, the signal may be filtered again if necessary and then it will be output through a speaker operating within the range of human hearing.

8.2. Characteristics

8.2.1. Functional / Performance Requirements

8.2.1.1. Signal to Noise Ratio

The transferred signal from the ultrasonic radio shall have at least a 60 dB signal to noise ratio.

Rationale: Typical audio equipment that functions well has a signal to noise ratio of at least 60 dB. Very good audio equipment has even higher decibels. Since the ultrasonic radio should have a clear signal so communications can happen cleanly 60 dB is required.

8.2.1.2. Transmission Distance

The ultrasonic radio shall meet a communication distance of 15 meters or more.

Rationale: Although a long transmission distance for the ultrasonic radio is better, there are limitations from testing and the ultrasonic nature of the waves. Knowing this, a transmission distance of 15 meters or more will allow for a usable and testable ultrasonic radio.

8.2.1.3. Total Harmonic Distortion

The ultrasonic radio shall have a total harmonic distortion of less than or equal to 5%.

Rationale: It is important to keep total harmonic distortion low to keep good audio quality. Typically, a total harmonic distortion level less than or equal to 5% is acceptable and is the goal for this ultrasonic radio.

8.2.2. Physical Characteristics

8.2.2.1. Mass

The mass of the ultrasonic radio shall be less than or equal to 10 kilograms.

Rationale: While there isn't a specific weight requirement for the ultrasonic radio, it should be relatively easy to move around for maximum use. A weight of up to 10 kilograms should be easy for any military man/woman to move.

8.2.3. Electrical Characteristics

8.2.3.1. Inputs

The electrical inputs should not be changed by users of the ultrasonic radio. All tests will be performed under these conditions and system performance under separate conditions is not guaranteed.

8.2.3.1.1 Power Consumption

The maximum peak power of the system shall not exceed 4.5 watts.

> *Rationale: This requirement is due to the power of the system being provided by a USB wall adapter. The maximum power provided by USB 3.0 is 4.5 watts, so that is the maximum power limit.*

8.2.3.1.2 Input Voltage Level

The input voltage level for the ultrasonic radio shall be +5 VDC.

> *Rationale: USB wall adapter has a voltage level of 5 VDC which will be used to power the ultrasonic radio.*

8.2.3.1.3 Input Current Level

The input current for the ultrasonic radio shall not exceed 900 mA.

> *Rationale: 900 mA is the maximum current that can be supplied by the USB 3.0 wall adapter and is thus the maximum current that can be supplied to the ultrasonic radio.*

8.2.3.1.4 Voice Input

The ultrasonic radio shall take user voice input that operates from 100 Hz to 3 kHz.

> *Rationale: The ultrasonic radio needs to be able to handle any range of human voice frequencies and transmit them.*

8.2.3.2. Outputs

8.2.3.2.1 Voice Output

The ultrasonic radio shall output the voice input up to 15 meters away at frequencies 100 Hz to 3 kHz.

> *Rationale: The ultrasonic radio will allow communications to pass into the microphone and out through the output speaker a distance up to 15 meters away to satisfy the conditions of a radio.*

8.2.4. Environmental Requirements

The ultrasonic radio shall be designed to withstand and operate in the environments and laboratory tests specified in the following section.

Rationale: This is a requirement specified by the intended usage of the ultrasonic radio

8.2.4.1. Pressure (Altitude)

The ultrasonic radio may be able to operate up to 2.5 atm of pressure.

Rationale: The internal pressure of a typical military submarine is roughly equivalent to 2.5 atm. Thus, to perform its function, the ultrasonic radio should be able to function up to this amount of pressure.

8.2.4.2. Thermal

The ultrasonic radio may be able to operate at thermal temperatures ranging from 55 degrees Fahrenheit to 95 degrees Fahrenheit.

Rationale: The internal thermal temperatures of a military submarine without power can range from 55 degrees Fahrenheit to 95 degrees Fahrenheit in extreme scenarios. So, the ultrasonic radio should be able to function in these emergencies.

8.2.4.3. Humidity

The ultrasonic radio should be able to function in 0-95% relative humidity.

Rationale: The internal relative humidity of a military submarine without power can range from 0-95% relative humidity in extreme scenarios. So, the ultrasonic radio should be able to function in these emergencies.

8.2.5. Failure Propagation

3.2.5.1 Recovery

The Ultrasonic radio should provide a way to reset the entire system.

Rationale: This is a feature of the radio that should help fix errors that occur with the ultrasonic radio.

9. Support Requirements

4.1.1 Ultrasonic Radio Manual

To help users understand how to use the ultrasonic radio, a manual that details some of the parts of the radio and generally how to use it will be provided to customers.

Rationale: This feature will help users better understand the ultrasonic radio which will allow for improved usage of the device.

4.1.2 Power Adapter

Users of the ultrasonic radio will be provided with a USB power adapter to power the radio. However, clients must have access to a wall outlet to use the USB adapter and power the radio.

Rationale: Providing the power adapter will ensure that the correct power source is used for the ultrasonic radio. It will also allow the users to spend less time before the radio is operational.

Appendix A: Acronyms and Abbreviations

ATM	Atmosphere
CONOPS	Concept of Operations Document
dB	Decibels
Hz	Hertz
ICD	Interface Control Document
Kg	kilograms
kHz	Kilohertz (1,000 Hz)
mA	Milliamp
MHz	Megahertz (1,000,000 Hz)
SNR	Signal to Noise Ratio
USB	Universal Serial Bus
VDC	Direct Current Voltage

Appendix B: Definition of Terms

Electromagnetic waves	Waves produced by the movement of electric charge and the propagation of electric and magnetic fields.
Electromagnetic radiation	When electromagnetic waves interfere with each other when they should not
Receiver	Equipment that accepts transmitted waves carrying signals from another location
Transmitter	Equipment that generates and transmits waves carrying signals to another location
Ultrasonic	A range of frequencies from 20 kHz to 20 MHz

Ultrasonic Radio
Nathan Cinocca

INTERFACE CONTROL DOCUMENT

REVISION – Draft
28 September 2023

INTERFACE CONTROL DOCUMENT
FOR
Ultrasonic Radio

PREPARED BY:

Team 84

APPROVED BY:

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Nathan Cinocca Date

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John Lusher II, P.E. Date

____
T/A Date

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Table of Contents

List of Tables

No table of figures entries found.

List of Figures

10. Overview

This Interface Control Document (ICD) will provide detail on how the various subsystems of the ultrasonic radio will function together. This document will also detail physical descriptions of various subsystems of the ultrasonic radio. The Interface Control Document will also explain how the subsystems will interface together to meet the requirements explained in the Functional System Requirements document and ConOps document.

11. References and Definitions

11.1. References

Refer to section 2.2 in the Functional System Requirements document.

11.2. Definitions

ATM	Atmosphere
CONOPS	Concept of Operations Document
dB	Decibels
Hz	Hertz
ICD	Interface Control Document
Kg	kilograms
kHz	Kilohertz (1,000 Hz)
mA	Milliamp
MHz	Megahertz (1,000,000 Hz)
Mm	Millimeter
mW	Milliwatt
SNR	Signal to Noise Ratio
TBD	To be determined
USB	Universal Serial Bus
VDC	Direct Current Voltage
W	Watt

12. Physical Interface

12.1. Weight

The overall weight of the system is difficult to determine at the current time as many of the subsystems have not been designed yet. The design of the systems will determine how many transistors, resistors, capacitors, and operational amplifiers will be used. All these components are light and should not add excessive weight. The heaviest subsystem in the ultrasonic radio will be the speakers and microphones. Although the speakers and microphones will be heavier compared to the transistors and other circuit elements, they are still quite small and light. Thus, it should not be difficult to keep the entire radio under 10 kilograms.

12.2. Dimensions

The dimensions of the entire ultrasonic radio should be kept under 1 cubic foot in size.

Similar to the weight section, since many subsystems are still being designed it is difficult to give accurate dimensions for each of the subsystems. However, most of the components are quite small. For example, the 2N3904 transistor which will be used is 36 mm x 18 mm x 1.5 mm. So, even using 100 transistors will still allow lots of space for the microphones, operational amplifiers, and other circuit elements. Op amp 743, which will be used in filters, and modulation/demodulation circuits has dimensions of 356 mm x 356 mm x 35 mm, which again is small even if many are used. Currently, the microphones and speakers that are being considered are also small at about 10 mm x 10mm x 3.5 mm. Since all the parts are small the ultrasonic radio should be able to meet the dimension requirement of 1 cubic foot.

13. Thermal Interface

Since the ultrasonic radio will be functioning at relatively low power, it will not need any heat sink to maintain low heat and high efficiency.

14. Electrical Interface

14.1. Primary Input Power

The ultrasonic radio has a maximum power of 4.5 watts. More specifically this is 5 V and 900 mA of current supplied by a USB 3.0 adapter. Although the power supplied to each subsystem is TBD at this point, since most are being designed, some maximum power requirements can be determined. This will be discussed in section 5.2.

14.2. Voltage and Current levels

- Signal amplifiers shall have no more than 50 mA and 5 V for 250 mW of power
- Filters shall have no more than 15 mA and 5 V for 75 mW of power
- Modulator/demodulators shall have no more than 100 mA and 5 V for 500 mW of power
- Power amplifiers shall have no more than 300 mA and 5 V for 1.5 W of power
- Speaker and microphones shall have no more than 350 mA and 5 V for 1.75 W of power

15. Communications / Device Interface Protocols

15.1. Communications Safety

Although this radio operates at a frequency that can not be heard by the human ear. The ultrasonic radio can still cause hearing loss from excessive exposure to ultrasonic frequencies. Thus, clients that are using the ultrasonic radio for extended amounts of time should wear ear protection.

Ultrasonic Radio
Nathan Cinocca

SCHEDULE AND VALIDATION

REVISION – Draft
28 September 2023

Schedule

	October 2nd	October 9th	October 16th	October 23th	October 30th	November 6th	November 13th	November 20th
Design and simulate signal amplifier								
Power Amplifier Research								
Modulation/demodulation Research								
Order Parts								
Filter Design								
Signal Amplifier Test								
Design and simulate modulation/demodulation								
Power Amplifier Design								
Filter Test (For Modulation)								
Filter Test (For Demodulation)								
Test modulation/demodulation								
Power Amplifier simulation and test								
Completed Altium PCB								
All PCBs soldered								
Final Testing (Filters)								
Final Testing (Modulator)								
Final Testing (Demodulator)								
Final Testing (Power Amp)								

Completed Pending Not Started Behind Schedule

Validation

Paragraph #	Test Name	Success Criteria	Methodology	Status	Responsible Engineer(s)
3.2.1.1	Signal to Noise Ratio	The transmission signal from the transmitter to the receiver should have >= 60 dB signal to noise ratio	Test gain with an oscilloscope at the output node of the receiver	UNTESTED	Full Team
3.2.1.2	Transmission Distance	The signal should be able to transmit and be received at 15 meters or more	Send the signal and measure the maximum distance with a tape measure	UNTESTED	Full Team
3.2.1.3	Total Harmonic Distortion	The output signal should have a total harmonic distortion less than or equal to 5%	Test the output total harmonic distortion at the output node of the radio with an oscilloscope	UNTESTED	Jacob Ralls
3.2.2.1	Mass	Have the entire ultrasonic radio be less than or equal to 10 kilograms	Weigh all PCBs that make up the radio on a scale	UNTESTED	Full Team
3.2.3.1.1	Power Consumption	The maximum peak power of the system shall not exceed 4.5 watts	Use multimeter to check power consumption of ultrasonic radio	TESTED	Full Team
3.2.3.1.2	Input Voltage Level	The input voltage level for the ultrasonic radio shall be +5 VDC	Use multimeter to check voltage levels of ultrasonic radio	TESTED	Full Team
3.2.3.1.3	Input Current Level	The input current for the ultrasonic radio shall not exceed 900 mA	Use multimeter to check current levels of ultrasonic radio	UNTESTED	Full Team
3.2.3.1.4	Voice Input	The ultrasonic radio shall take user voice input that operates from 100 Hz to 3 kHz	Test input microphone with different voice frequency recording within the 100 – 3kHz range	UNTESTED	Nathan Cinocca
3.2.3.2.1	Voice Output	The ultrasonic radio shall output the voice input up to 15 meters away at frequencies 100 Hz to 3 kHz	Test output speaker with different voice frequency recording within the 100 – 3kHz range	UNTESTED	Jacob Ralls
3.2.4.1	Pressure (Altitude)	The ultrasonic radio may be able to operate up to 2.5 atm of pressure	Use ultrasonic radio in a container with higher pressure	UNTESTED	Full Team
3.2.4.2	Thermal	The ultrasonic radio may be able to operate at thermal temperatures ranging from 55 degrees Fahrenheit to 95 degrees Fahrenheit	Use ultrasonic radio outside or in a temperature-controlled area such as oven	UNTESTED	Full Team
3.2.4.3	Humidity	The ultrasonic radio should be able to function in 0-95% relative humidity	Use a container with controlled humidity to test ultrasonic radio	UNTESTED	Full Team
3.2.5.1	Recovery	The Ultrasonic radio should provide a way to reset the entire system	Test reset button to see if it turns off and resets the ultrasonic radio	UNTESTED	Full Team

Ultrasonic Radio

Jacob Ralls & Nathan Cinocca

Subsystem Reports

REVISION – Draft
3 December 2023

Functional System Requirements
for
Ultrasonic Radio

Prepared by:

Jacob Ralls & Nathan Cinocca 12/3/2023

Author Date

Approved by:

Nathan Cinocca 12/3/2023

Project Leader Date

John Lusher, P.E. Date

T/A Date

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Table of Contents

List of Tables

List of Figures

1. Introduction

The Ultrasonic Radio plays a pivotal role in revolutionizing communication technologies by introducing an innovative approach to data transmission. The primary objective of this system is to establish reliable communication channels in environments sensitive to electromagnetic interference. By utilizing ultrasonic frequencies and acoustic waves, this subsystem mitigates the challenges posed by traditional electromagnetic wave-based communication systems. The system is broken down into the signal amplifier, filter, modulator, demodulator, and power amplifier. The subsystems are the key components within the broader framework of the Ultrasonic Radio project, as outlined in the Concept of Operations (ConOps), Functional System Requirements (FSR), and Interface Control Document (ICD).

2. Transmitter Side

2.1. Low Frequency Filter

2.1.1. Subsystem Introduction

The Low Frequency Filter is the first component that the incoming audio will pass through in the ultrasonic radio. The goal of the low frequency filter is to lessen any noise that occurs outside of a typical human's hearing/speaking range. More specifically, the filter should operate within the frequency range of roughly 100 Hz to 3300 Hz. Frequencies outside this range should be diminished to allow for a clearer audio signal to pass through the radio.

2.1.2. Subsystem Details

As previously mentioned, this low frequency filter needs to operate with gain around 1 V/V for frequencies from 100 Hz up to 3300 Hz. Additionally, with a total allowable current for the ultrasonic radio of 900 mA, the goal was to keep the current low for this circuit. The two images below show the schematic (Figure 1) of the low frequency filter and the resulting PCB (Figure 2) that was tested.

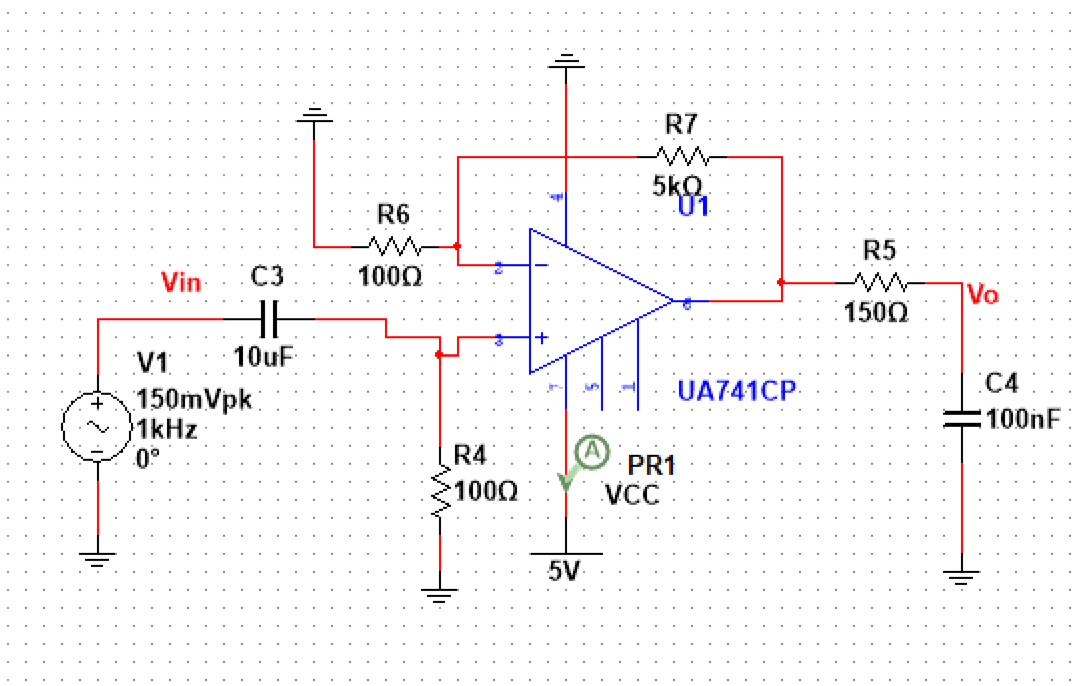

Figure 1: Low Frequency Filter Schematic

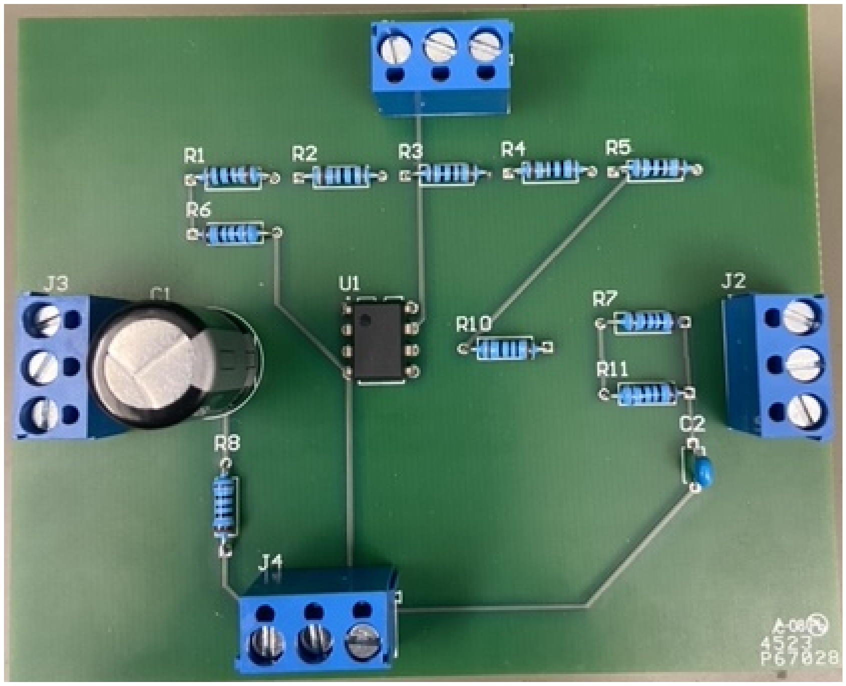

Figure 2: Low Frequency Filter PCB

2.1.3. Subsystem Validation

When testing the low frequency filter, I looked at the voltage consumed, current consumed, and bode plot of the circuit. As shown in Figure 3, The circuit operates with the required 5 V and it uses very low current at 2 mA. Thus the circuit easily meets the power requirements.

Figure 3: Low Frequency Filter Power Consumption

However, when testing the circuit, I ran into trouble with the frequency response shown in the bode plots. As shown in Figure 4, the frequency response of the low frequency filter was incredibly noisy and did not display the proper response. After discussing with Dr. Lusher, analyzing my PCB, and analyzing my circuit design we have determined a few things to try to generate a better frequency response. The first is to check soldering connections. I am new to soldering and after looking at my PCB it appeared that there may have been some incorrectly soldered components. More specifically cold connections that did not fuse completely. Additionally, another solution to this issue could be to increase resistor values in my schematic. The low resistor values of R4, R6, and R7 in Figure 1 could have been causing unnecessary strain leading to bad values. Another possible solution may be to exchange the old 741 op amp that I am using for a newer op amp with better functionality. Finally, in order to make testing easier, I left long wires on my through hole resistors. These wires could be acting as antennas and ruining the signal of my circuit. To remedy this problem I will cut the wires shorter.

Figure 4: PCB Filter Frequency Response

Ultimately I am confident that the frequency response will improve when I try these different solutions. This is because my simulations, as shown in Figure 5, indicate a proper frequency response.

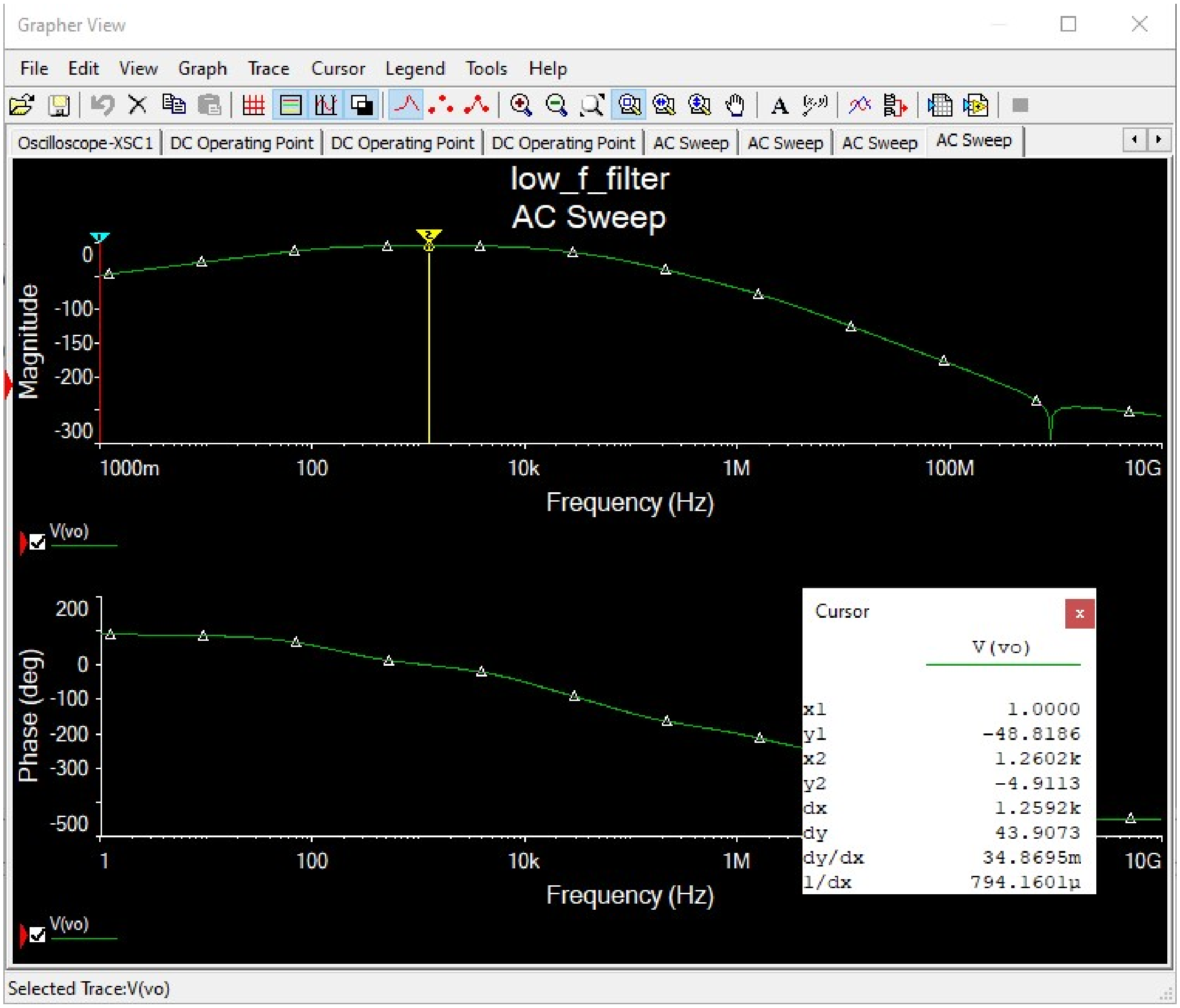

Figure 5: Low Frequency Filter Simulated Frequency Response

2.1.4. Subsystem Conclusion

In conclusion, the dc power of the low frequency filter worked as expected. However, the frequency response was very noisy when compared to simulations and needs to be addressed. Once I have tried all of the possible solutions mentioned above, the frequency response will most likely resemble the simulations.

2.2. Signal Amplifier

2.2.1. Subsystem Introduction

The signal amplifier is the second stage on the transmitter side of the ultrasonic radio. The goal of the signal amplifier is to increase the strength of the incoming signal after various unwanted noise has been filtered out. The amplified signal will then be able to move through the next stage of the ultrasonic radio more easily.

2.2.2. Subsystem Details

The precise value of the signal amplifiers gain is not exceedingly important. As such I decided that a gain of around 20 dB - 25 dB would be an effective amplification. Additionally, even though the low frequency filter will help to lessen noise at other frequencies, the signal amplifier should still operate within the 100 Hz to 3330 Hz range. Finally, just like the low frequency filter, the goal was to maintain relatively low current as the maximum allowed current is 900 mA. The resulting signal amplifier design is shown in Figure 6 and the PCB that was tested is displayed in Figure 7.

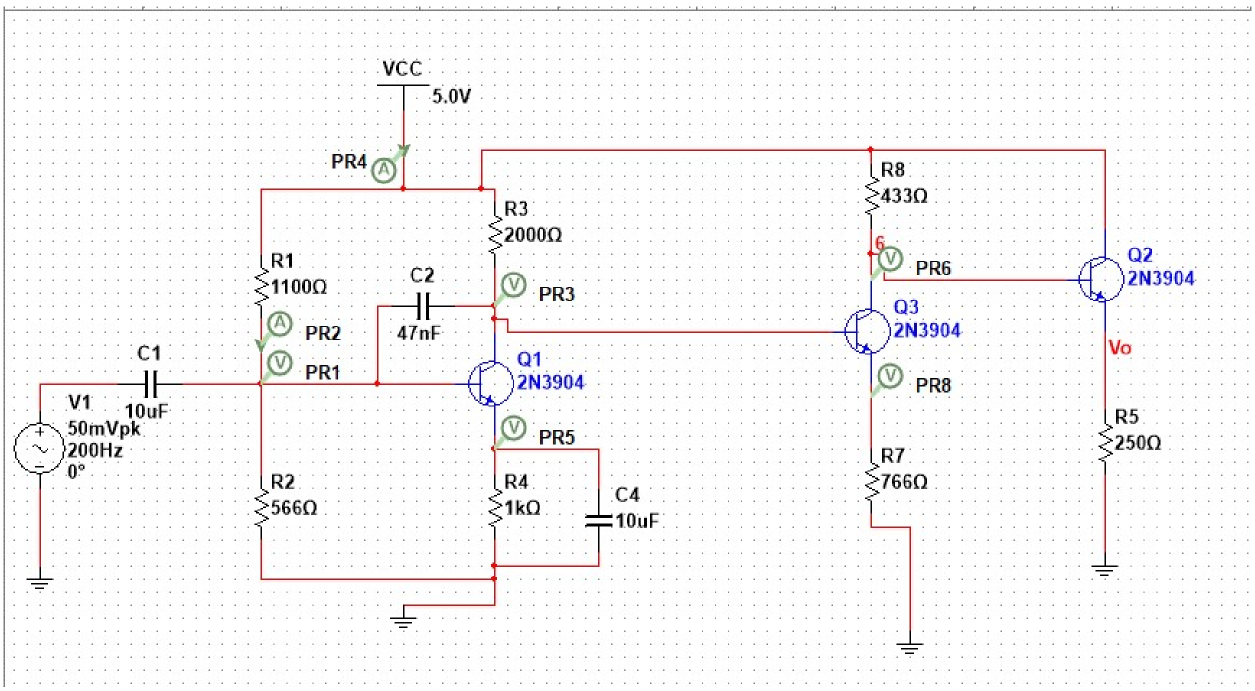

Figure 6: Signal Amplifier Schematic

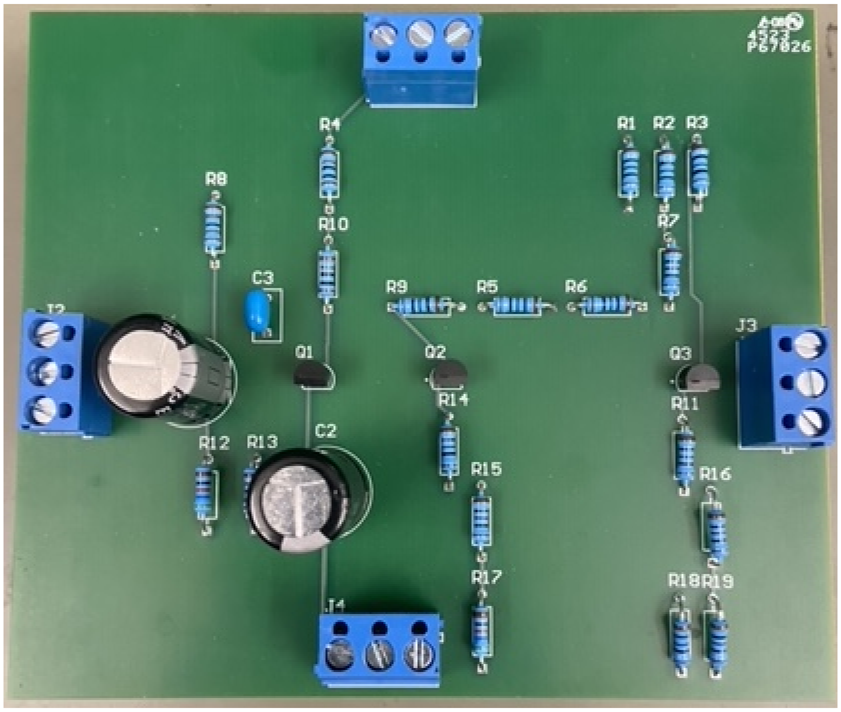

Figure 7: Signal Amplifier PCB

2.2.3. Subsystem Validation

The power consumption of the signal amplifier operated as expected according to the simulations. As shown in Figure 8, the signal amplifier consumed 17 mA and used 5 V. This 85 mW of power is very acceptable considering the maximum power allowed is 4.5 A.

Figure 8: Signal Amplifier PCB Power Consumption

However, similarly to the low frequency filter, the signal amplifier had issues with the frequency response. The first pole is relatively accurate at around 1000 Hz, but the second pole is at an exceedingly high frequency of around 10 MHz. This functionality is not what was expected. Additionally, the gain is very low at approximately 0 dB.

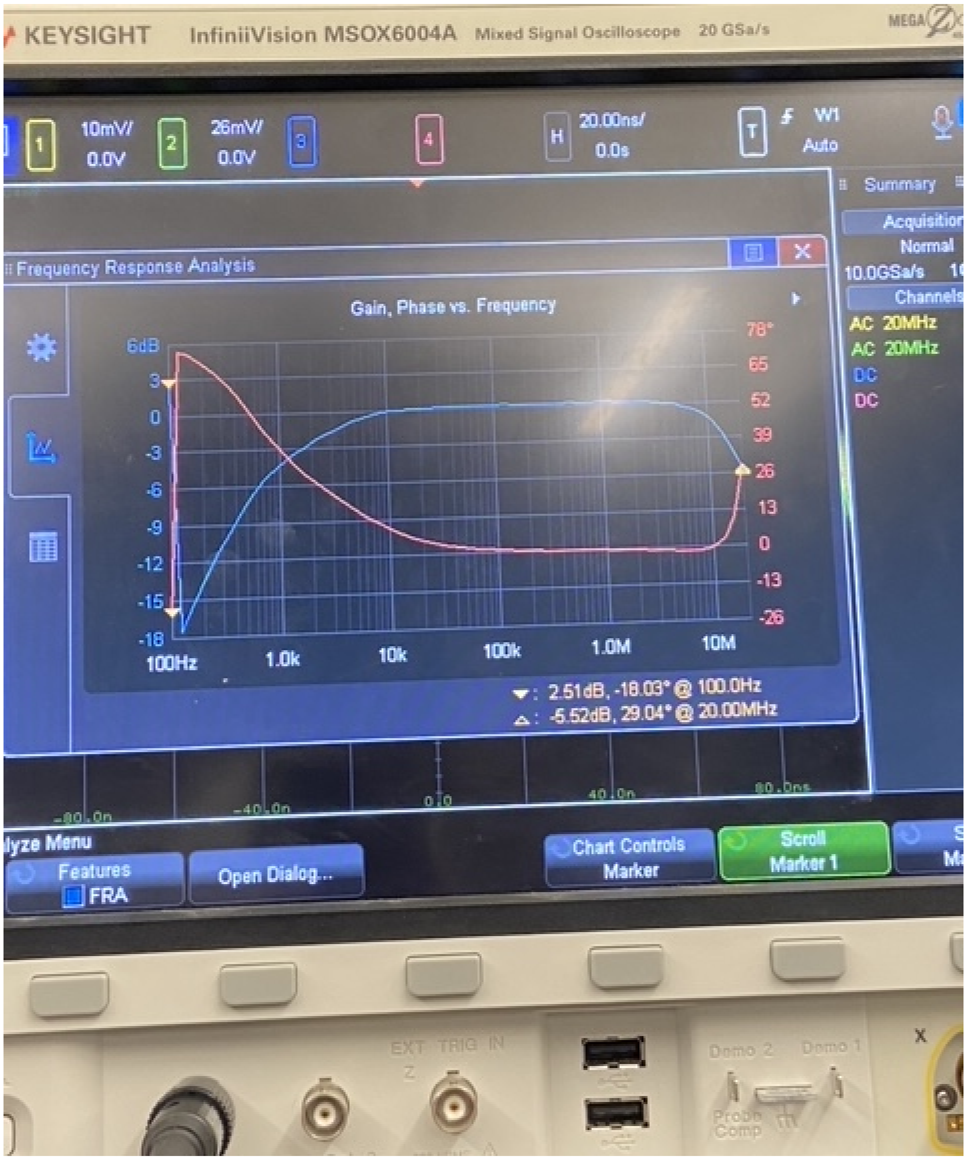

Figure 9: Signal Amplifier PCB Frequency Response

The PCB response is very strange as in simulations (Figure 11) the gain was roughly 27 dB and operated in the designated region of 100 Hz to 3300 Hz. Additionally, I tested the signal amplifier on a breadboard (Figure 10) and although the gain was lower than the simulations the operating frequency range was exactly the same as the simulations. This difference indicates that likely there are some components not soldered correctly on the signal amplifier PCB. This is likely the case since a PCB should have much better characteristics when compared to an old breadboard. Also, like the low frequency filter, my through hole components were acting as antennas. Once I cut those wires and fix the soldering connections the circuit should have a much better frequency response.

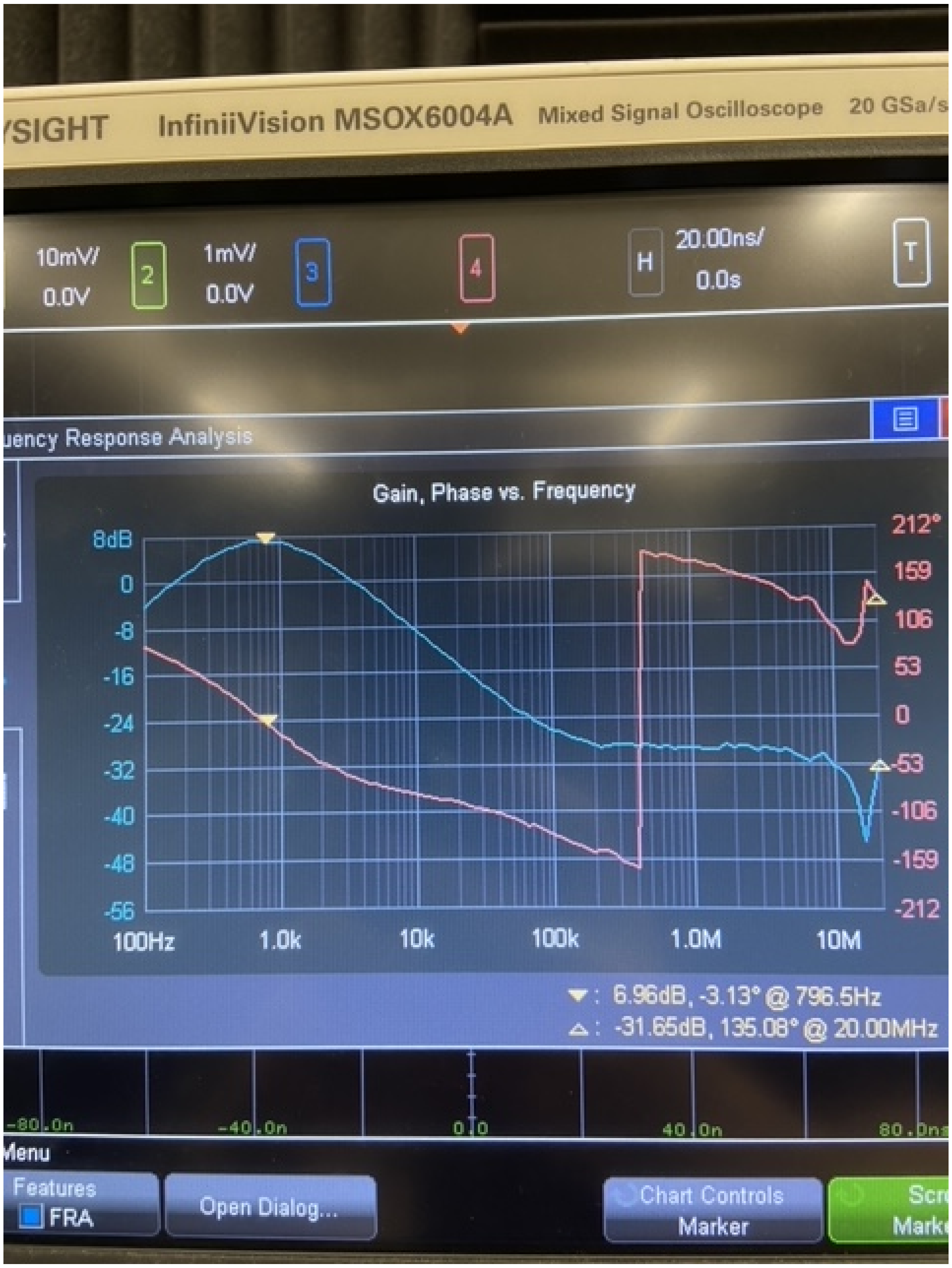

Figure 10: Signal Amplifier Breadboard Frequency Response

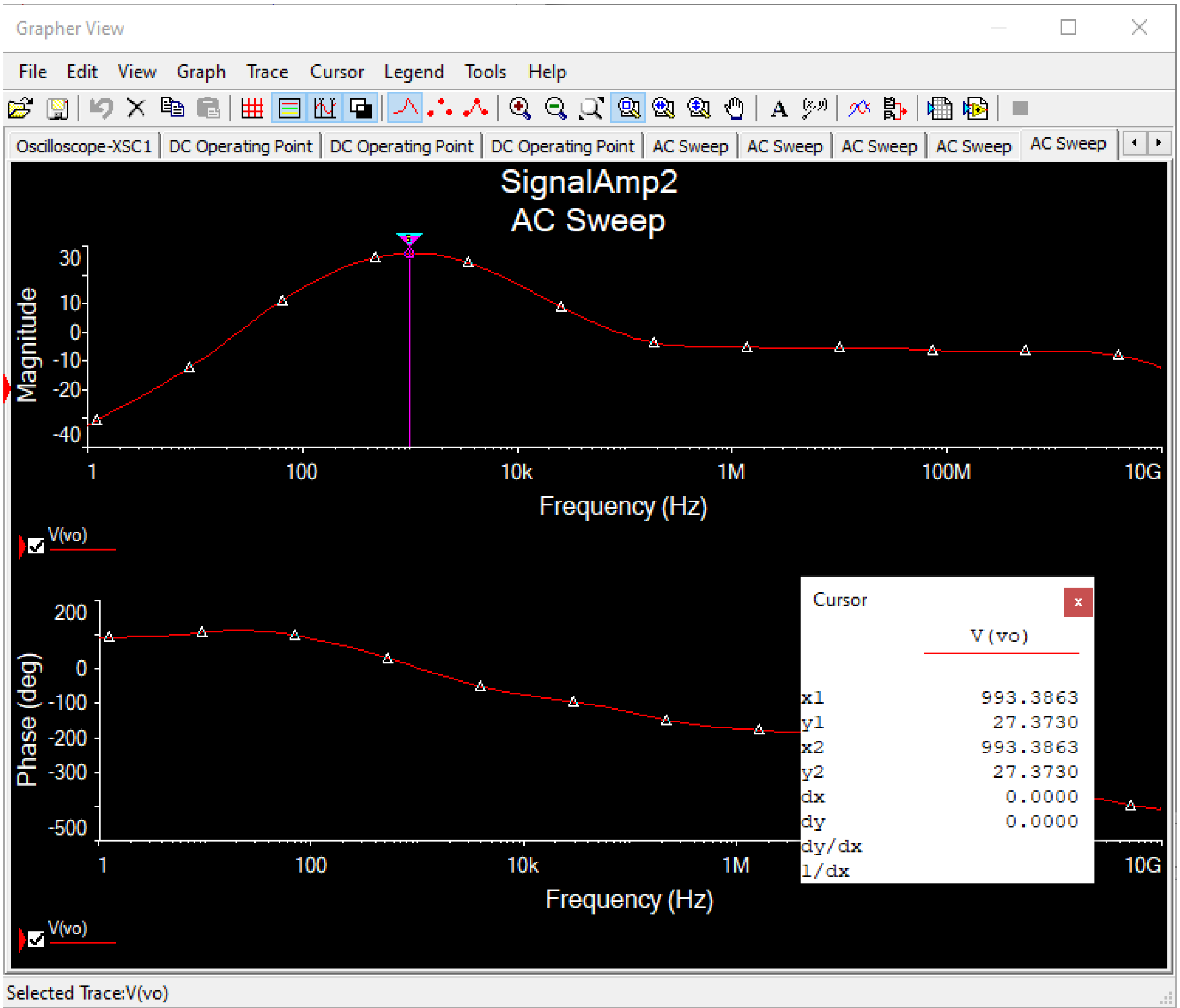

Figure 11: Signal Amplifier Simulated Frequency Response

2.2.4. Subsystem Conclusion

In conclusion, the dc power of the signal amplifier worked as expected. However, the frequency response had poor gain and frequency of operation when compared to simulations and needs to be addressed. Once I have tried all of the possible solutions mentioned above, the frequency response will most likely resemble the simulations and breadboard testing.

2.3. Frequency Modulator

2.3.1. Subsystem Introduction

After the audio signal is amplified in the signal amplifier, the signal travels through the frequency modulator. The frequency modulator is what creates the ultrasonic aspect of the ultrasonic radio. In other words, the frequency modulator changes the carrier frequency from a regular audio frequency (100 - 3300 Hz) to an ultrasonic frequency which is above 20 kHz. This will allow the information to travel faster and with more accuracy.

Frequency modulators change the frequency of the output signal based on the amplitude of the input signal. For this frequency modulator, the frequency will be modulated to around 50 kHz when the input signal has a low amplitude. The output signal will be at a lower frequency when the input signal amplitude is larger.

2.3.2. Subsystem Details

As stated before, the frequency modulator will modulate the incoming signal to around 50 kHz at its fastest frequency. Just like all the other subsystems the frequency modulator will use 5 V and work to maintain a low current usage so that the maximum current limit is not exceeded. Figure 12 shows the frequency modulator schematic and Figure 13 shows the frequency modulator PCB

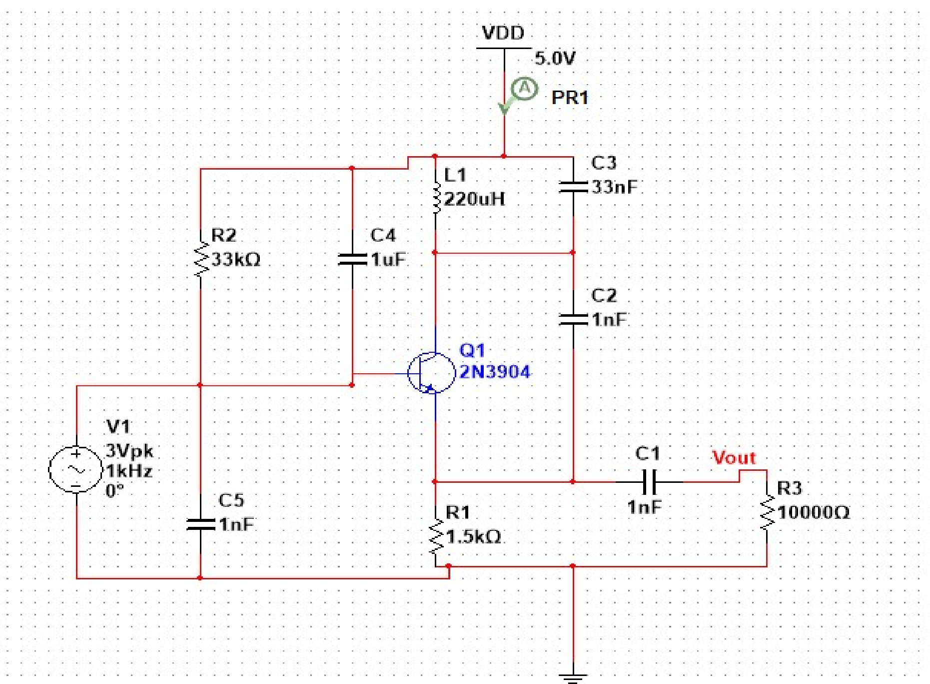

Figure 12: Frequency Modulator Schematic

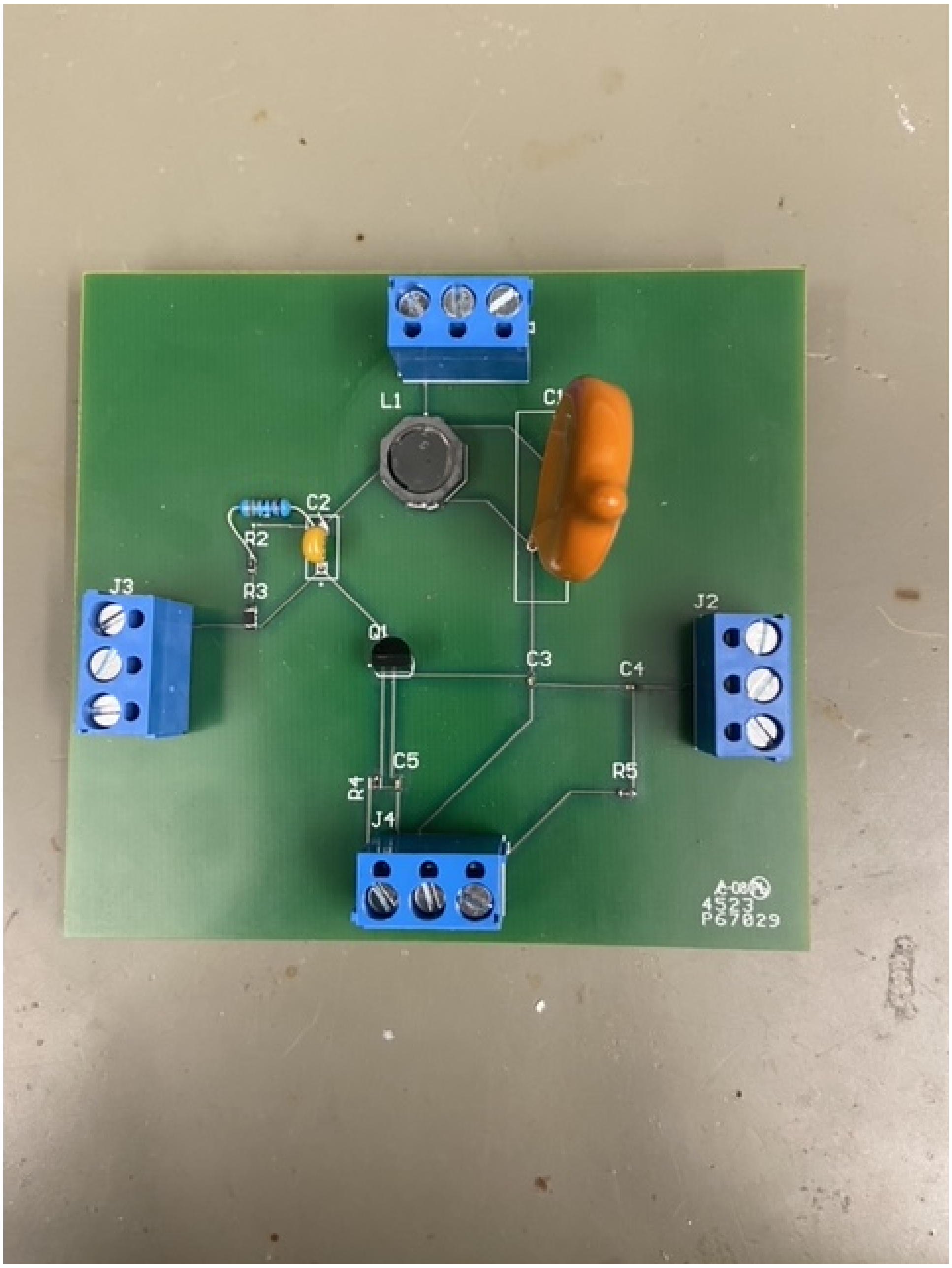

Figure 13: Frequency Modulator PCB

2.3.3. Subsystem Validation

The Frequency Modulator met the voltage and current requirements. As shown in Figure 14, the frequency Modulator used 5V and around 2 mA of current. This makes the power consumption very low and not a burden to the total ultrasonic radio.

Figure 14: Frequency Modulator Power Consumption

The transient simulation that shows how the input signal was modulated was very similar to simulations. The frequency modulator was tested with a 1 kHz sinusoidal wave input. The resulting output is shown in Figure 15 and 16. Figure 15 shows a zoomed out version of the output. Figure 16 allows the quicker frequency on the negative amplitude of the sinusoidal wave to be seen more clearly. Although the quicker modulated frequency is noisy because of its low amplitude, the frequency of the signal is around 50 kHz as expected.

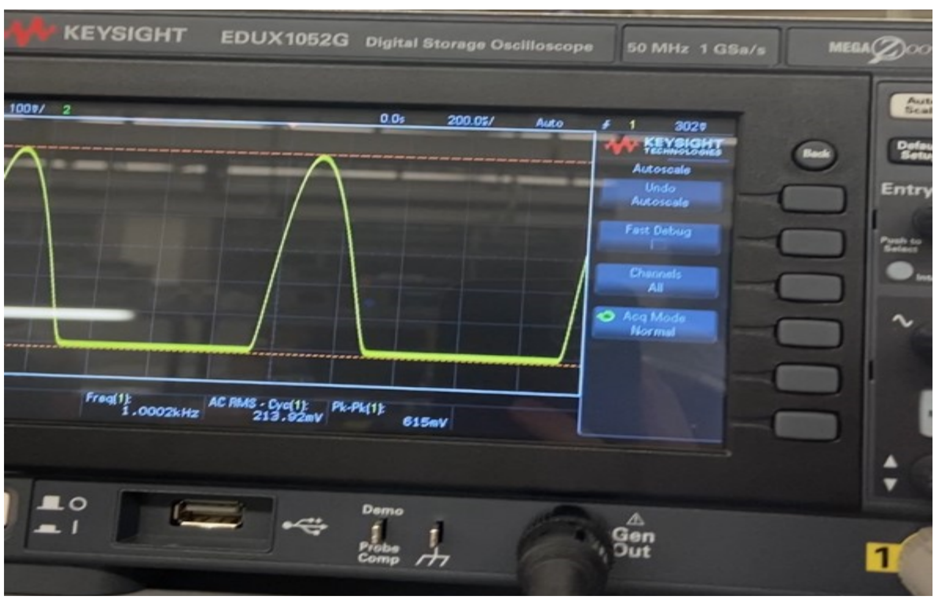

Figure 15: Frequency Modulator Transient 1

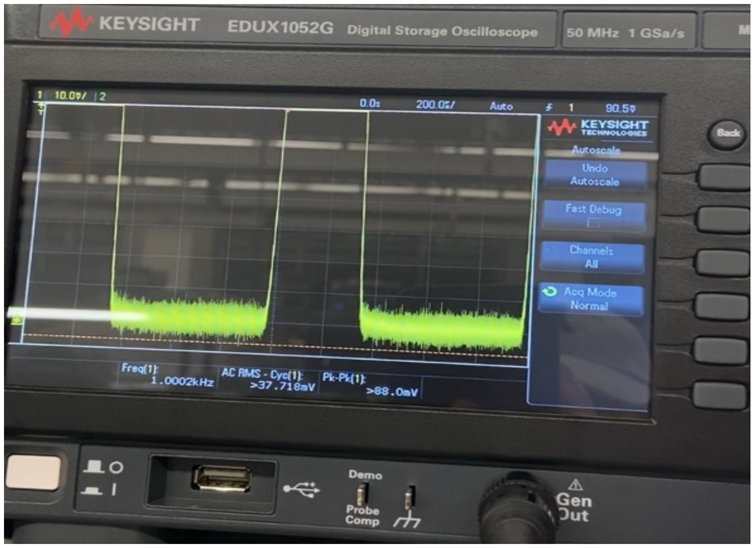

Figure 16: Frequency Modulator Transient 2

2.3.4. Subsystem Conclusion

For the most part, the frequency modulator functioned as I expected it to. The only problem is that the faster frequency is noisy. To fix this problem, I will start by examining soldering connections and fixing anything that is not completely connected. Next, I will try to alter some capacitor or inductor values to achieve a less noisy response. If none of these solutions work, the problem will most likely be solved by a large amplification so that the amplitude is larger and less impacted by noise. Thus, the issue should be resolved by a properly functioning power amplifier.

2.4. Power Amplifier

2.4.1. Subsystem Introduction

The final subsystem on the transmitter side of the ultrasonic radio is the power amplifier. The power amplifier increases the strength of the signal by a very large amount. This is important because the signal will attenuate and lose strength as it is being transmitted. If the signal loses too much power, it will be very difficult to receive and the signal to noise ratio will be very low. Additionally, since the signal will be transmitted acoustically and not through electromagnetic waves, there will be much higher attenuation than in usual communication methods.

2.4.2. Subsystem Details

Similarly to the other subsystems, the power amplifier will operate using 5 V while trying to use a low amount of current. The power amplifier should operate at 50 kHz or higher in order to properly amplify the modulated signal at around 50 kHz. Additionally, the gain at this frequency should be at least 100 dB in order to transmit the signal a sufficient distance. The schematic of the power amplifier is shown in Figure 17 and the PCB of the circuit is shown in Figure 18.

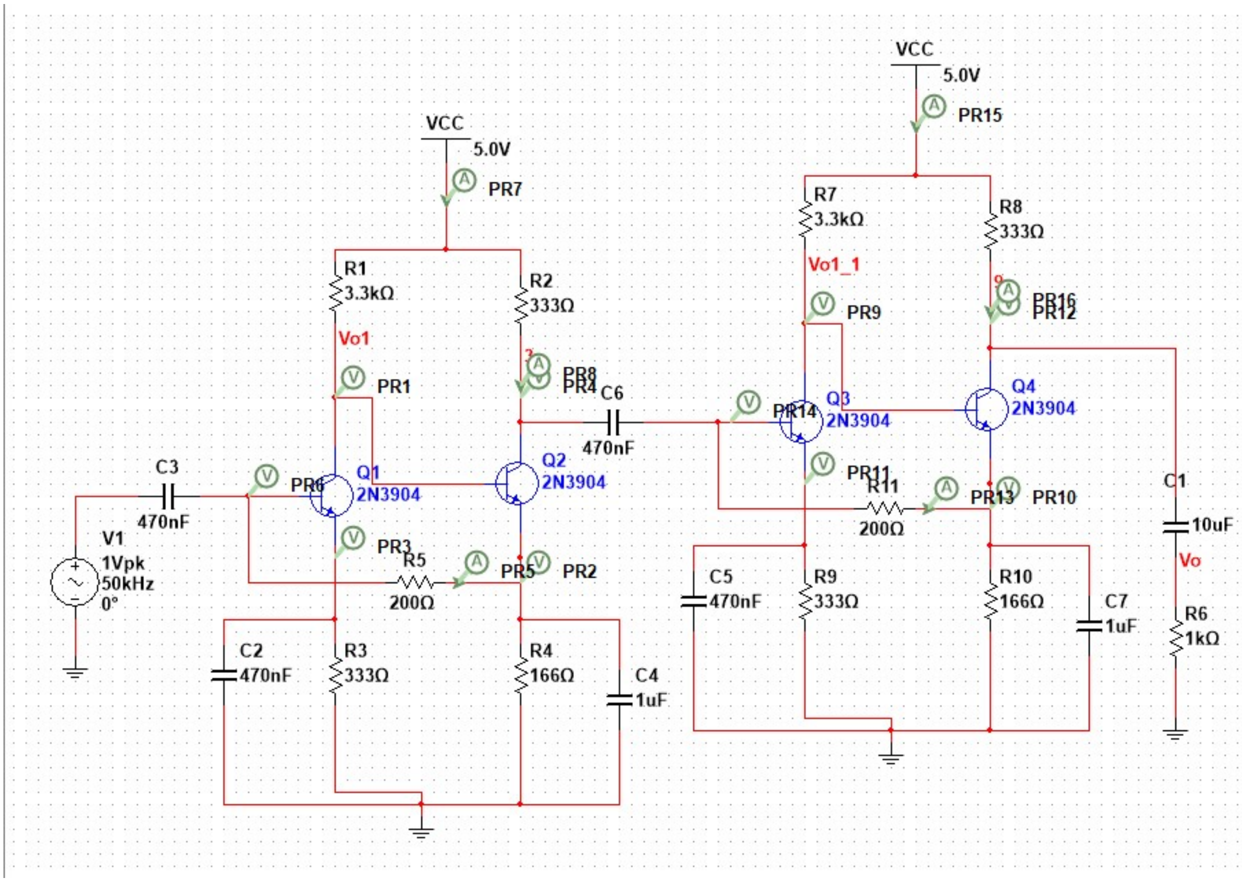

Figure 17: Power Amplifier Schematic

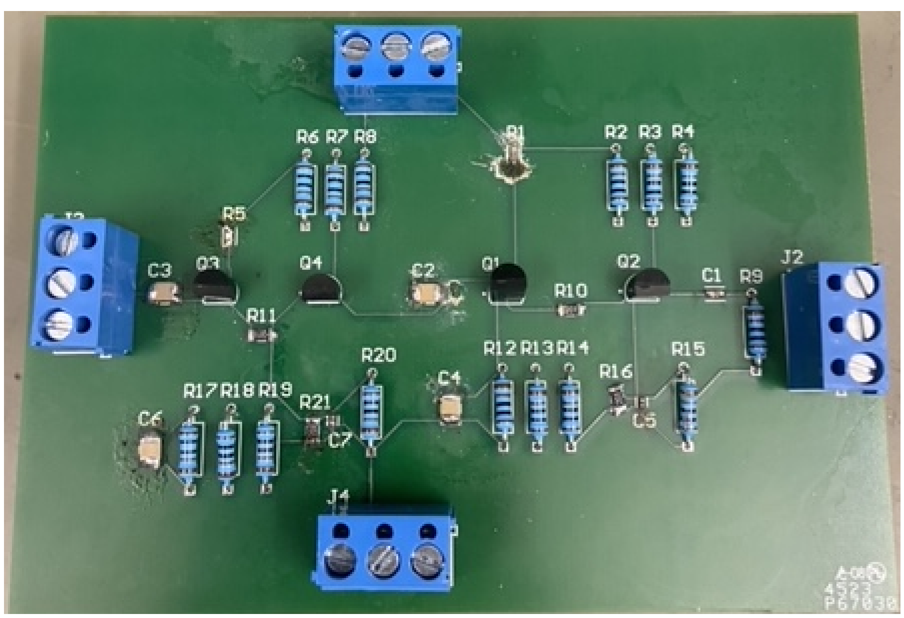

Figure 18: Power Amplifier PCB

2.4.3. Subsystem Validation

When testing the power amplifier PCB, it was able to meet the power consumption requirements. As shown in Figure 19, the power amplifier used the proper 5 V and used only 20 mA of current. Combined with the current consumption of the rest of the transmitter subsystems, the current consumption is well under the maximum 900 mA.

Figure 19: Power Amplifier Power Consumption

However, when testing the power amplifier, the gain of the frequency response (Figure 20) is much too low. The gain is only around 0 dB which is far below the 100 dB that was achieved in the simulation (Figure 21). The active frequency of the PCB test is fairly similar to the simulation. With the first pole of the power amplifier being around 10 kHz. Since only the gain seems to be off, I believe that again many of the components are not soldered correctly. This is most likely leading to many of the important resistive elements not providing the proper gain. On the other hand, the capacitive elements seem to be soldered correctly as the power amplifier is operating at the correct frequencies. If fixing incorrectly soldered components does not fix the power amplifiers gain, I may need to look into other solutions. However, the problem is most likely due to soldering issues.

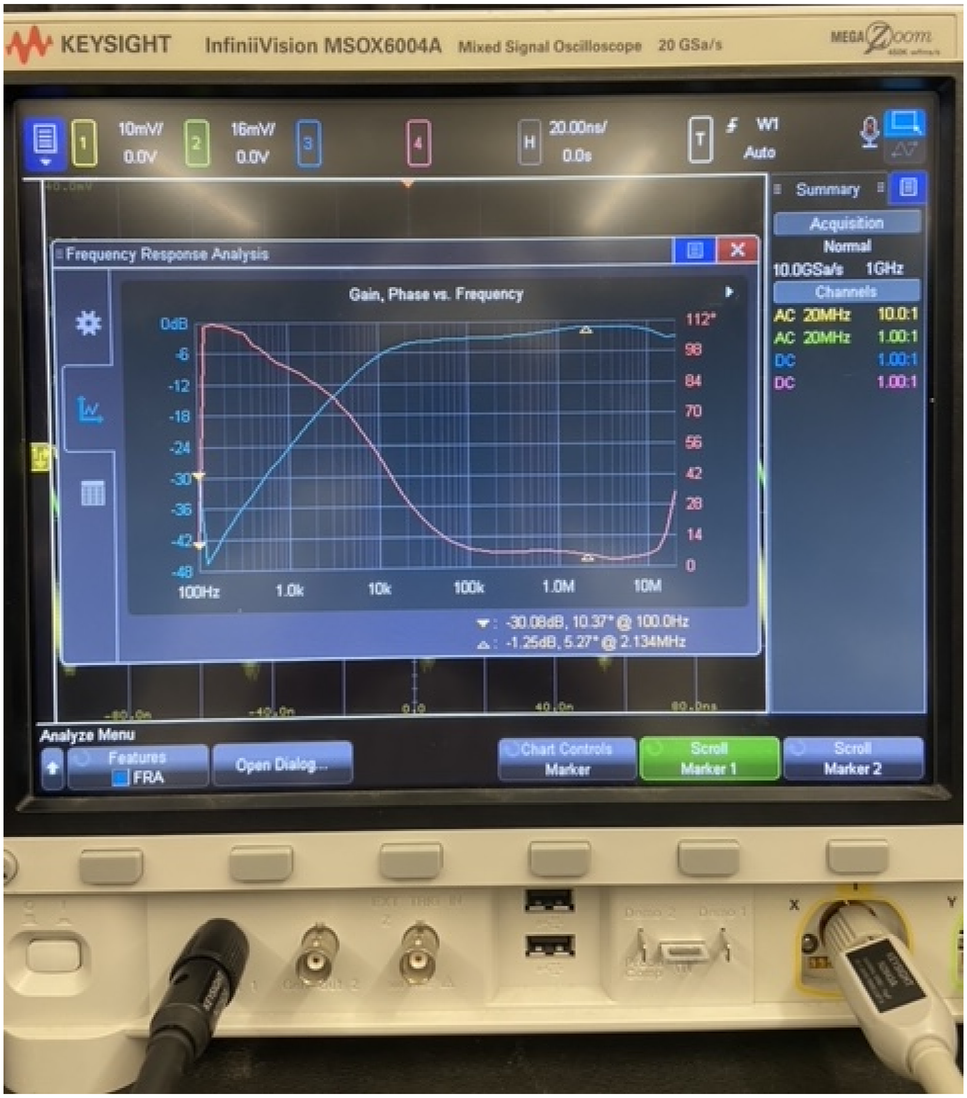

Figure 20: Power Amplifier PCB Frequency Response

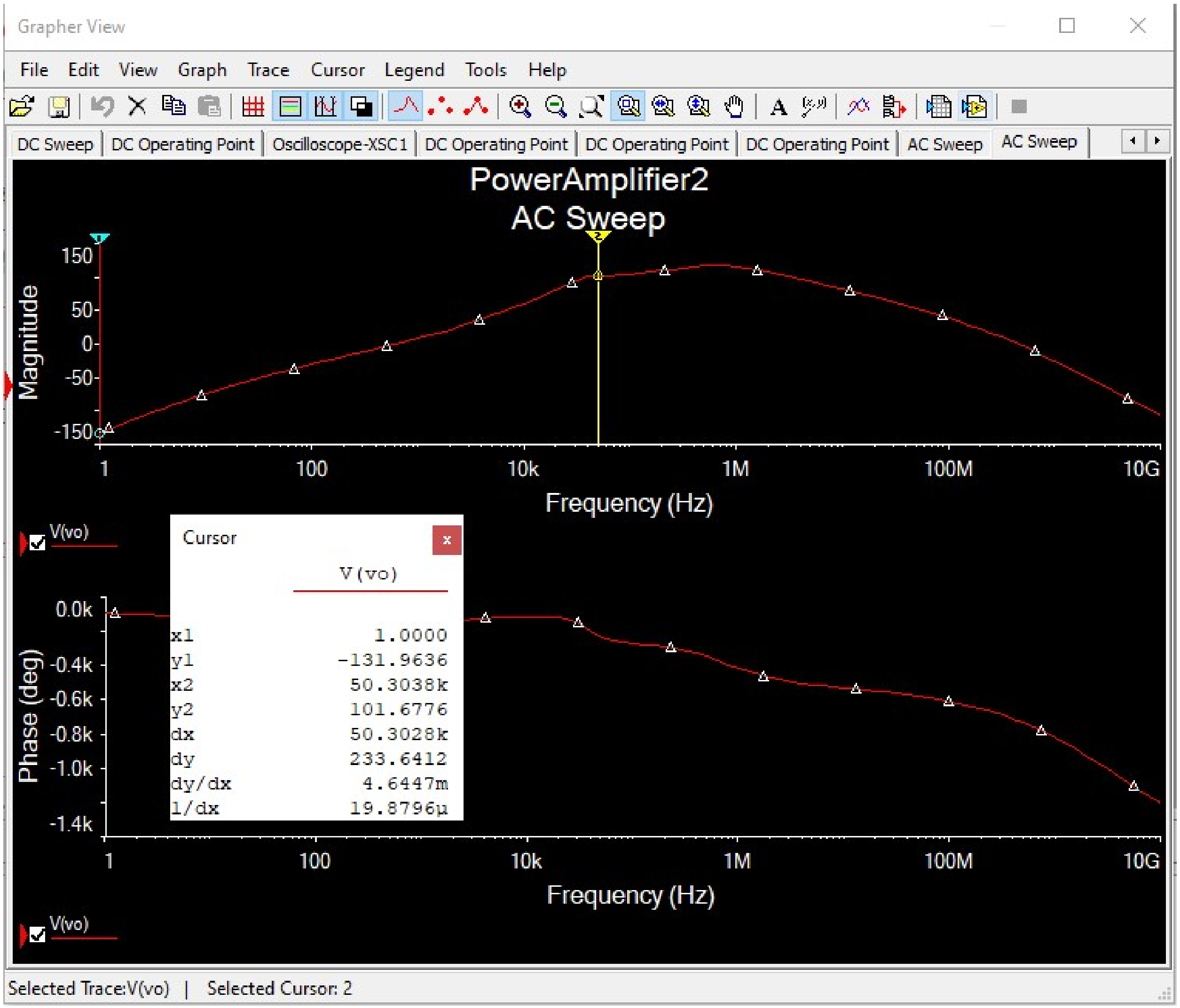

Figure 21: Power Amplifier Simulation Frequency Response

2.4.4. Subsystem Conclusion

In conclusion, the power requirements of the power amplifier were met. The power amplifier also operates within the proper frequency range, but the gain is far too low to properly transmit an audio signal. This will need to be fixed by resoldering faulty connections on the PCB. Additionally, I may need to make small changes to the power amplifier design to further improve the gain if it is still too low.

3. Receiver Side

This section will go over the receiver side of the Ultrasonic Radio project. This portion of the project is responsible for capturing, processing, and translating incoming ultrasonic signals back into audible communication. Let's break down the key subsystems involved in the receiver side.

3.1. Filter and Amplifier Subsystem

3.1.1. Subsystem Introduction

The Filter and Amplifier Subsystem on the receiver side of the Ultrasonic Radio project plays a crucial role in enhancing the quality and strength of the incoming ultrasonic signals before they undergo further processing. This subsystem is dedicated to ensuring that the received signals are clear, free from interference, and optimized for the subsequent stages of demodulation and conversion into audible communication. The filtering component of the subsystem aims to eliminate undesired noise or interference that may have been picked up during the transmission of ultrasonic signals. Along with the filtering process, the subsystem incorporates amplification mechanisms to boost the strength of the filtered signals. This is essential to ensure that the signals maintain clarity and integrity throughout the demodulation and conversion stages.

3.1.2. Subsystem Details

The circuit that was chosen was a 2nd order Chebyshev Bandpass Filter as this model allows for a specific range of frequencies to pass through while attenuating frequencies outside that range. A gain of roughly 20-40 dB was selected to ensure that weak ultrasonic signals are adequately amplified for further processing. As for the bandwidth, ultrasonic frequencies generally start above human hearing frequencies (20 kHz) and can operate at frequencies into several hundred kHz. However for this project the filter will only operate with a max of roughly 150 kHz. Below you can see the schematic for this circuit along with the corresponding bodeplot:

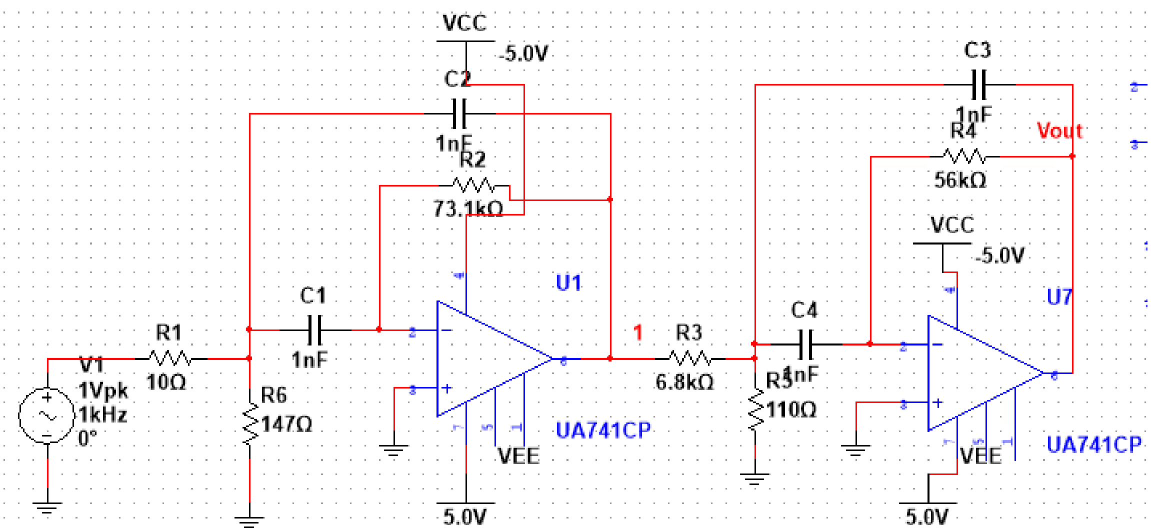

Figure 22: 2nd Order Chebyshev Bandpass Filter

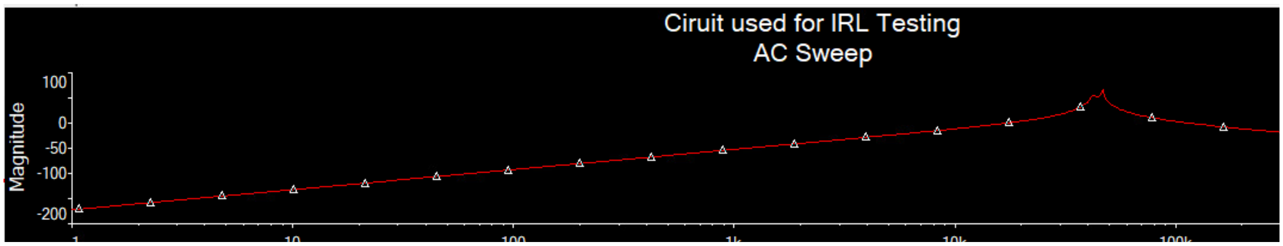

Figure 23: Simulated Bodeplot for designed BPF

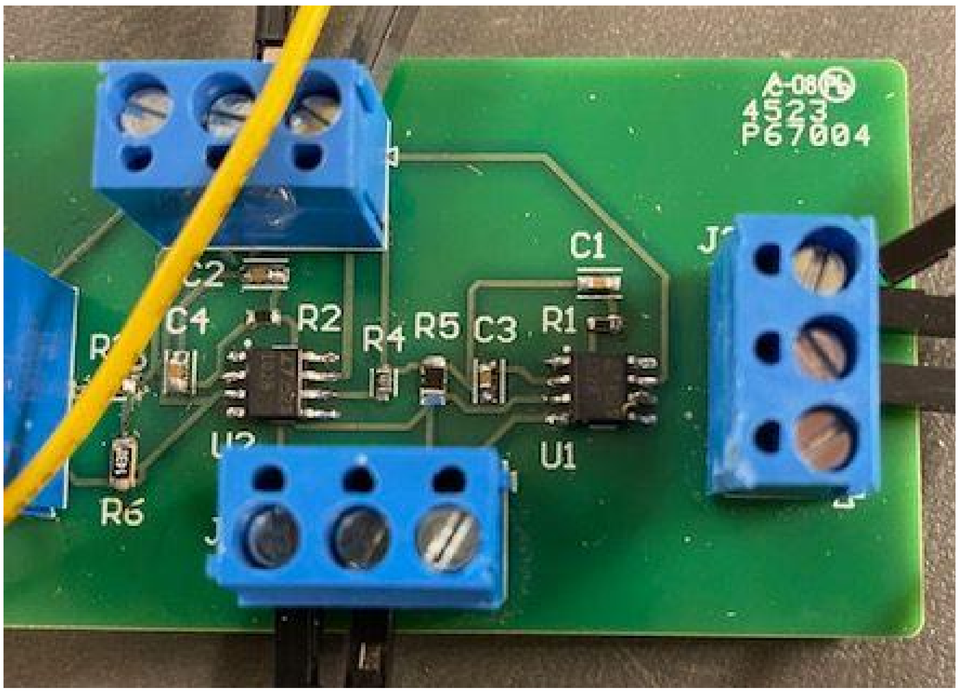

Figure 24: BPF PCB

3.1.3. Subsystem Validation

Before creating the PCB design, the circuit was tested extensively on a breadboard. In hindsight this was not the most optimal use of our time but some promising results regarding the peak gain did come out of it. Here was the bodeplot measured:

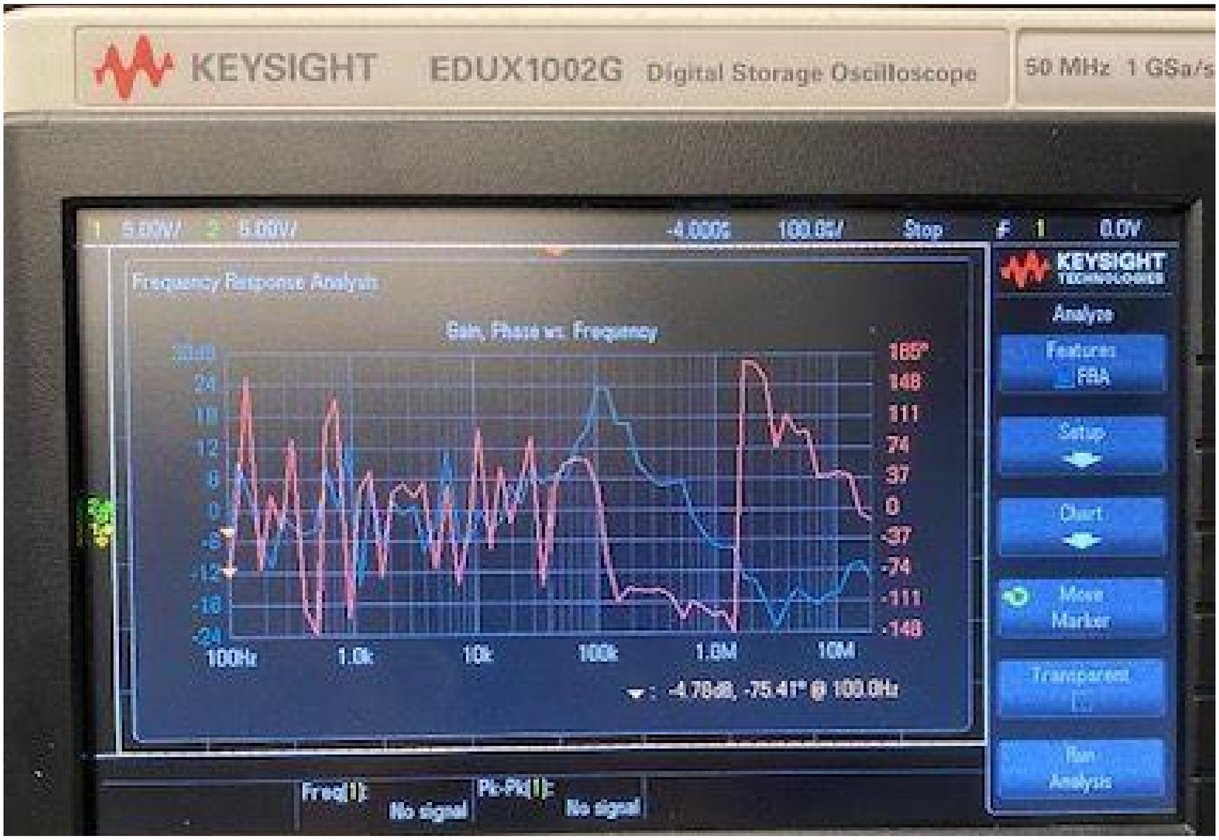

Figure 25: Bodeplot of Breadboard BPF

Table 1: BPF Table of Gain Values w.r.t. Frequency

Freq (Hz)	Gain (dB)
36.49k	5.65
44.72k	5.75
54.81k	6.41
67.18k	12.1
82.33k	17.39
100.9k	24.32
123.7k	23.04
151.6k	15.72
185.8k	11.86
227.7k	8.91

279.0k	3.26

From ***Table 1*** as well as ***Figure 22*** we can state that the design and testing of this bandpass filter worked when taking into account the amount of noise that the breadboard and LM741 op amps read as low end devices.

After the subsystem was designed on a PCB as shown in ***Figure 23***, it was then validated through the A2D Oscillator Bodeplot function. Below was the graph the plot produced:

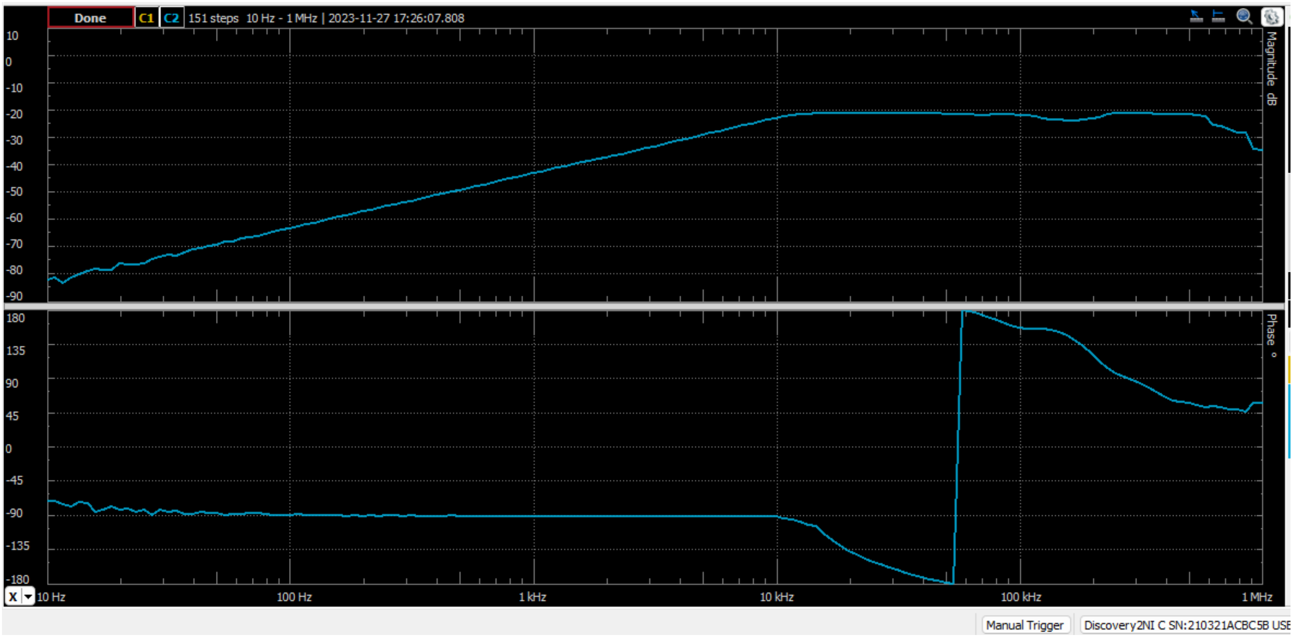

Figure 26: Bodeplot of the PCB BPF

It may be difficult to see in this image but the gain of the BPF does not adequately represent the peak gain we got in our simulations as well as our breadboard testing, maxing only at approximately -20 dB. A positive outcome from this graph is that the bandwidth matches our design in that it ranges from roughly 20 kHz to roughly 150 kHz when the graph reaches a relative min.

3.1.4. Subsystem Conclusion

We can safely state that the system is faulty when it comes to the expected gain. I did some more continuity tests and ensured that all pins of each electrical component were soldered correctly. To better verify that this circuit is designed properly, the subsystem was modeled in LTSpice instead of multisim. This is shown in the following figure:

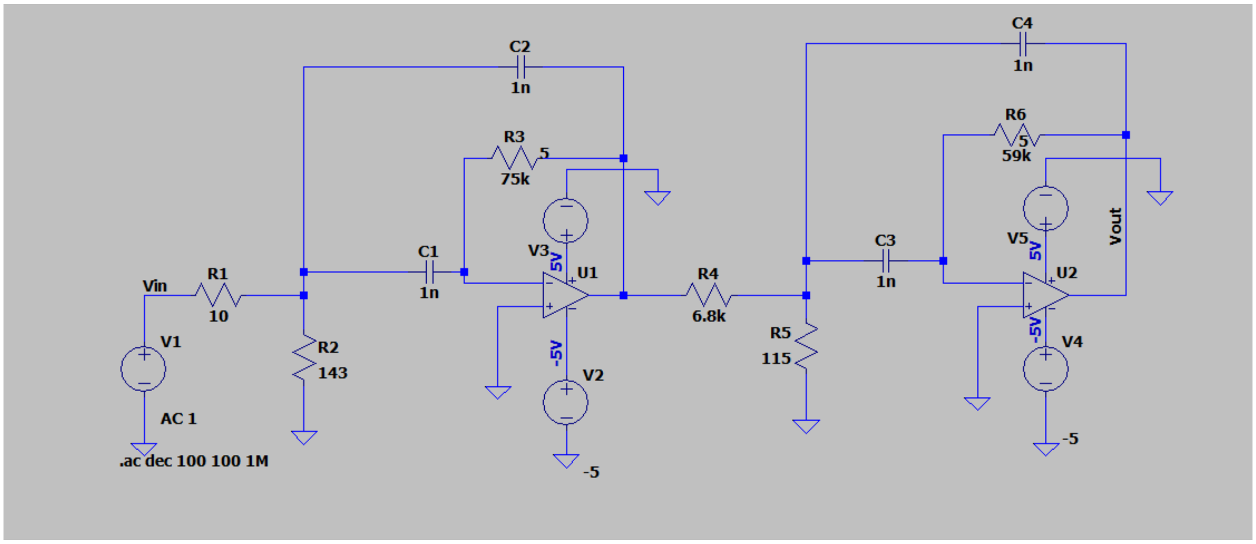

Figure 27: LTSpice Schematic of the Bandpass Filter

Running the simulation for this circuit does not give the expected results that we saw earlier. This is shown:

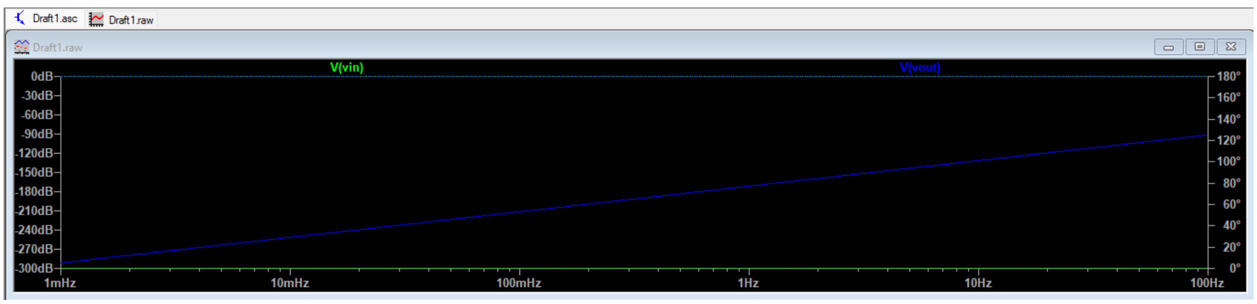

Figure 28: LTSpice Simulation of the Bandpass Filter

It is highly likely that this is due to an issue with the design in LTSpice as the designer is more familiar with the Multisim software than LTSpice. More trouble shooting will be done to get an acceptable graph.

Moving forward, if this subsystem ends up not working within LTSpice after trouble shooting has been done, it is highly likely that the resistor values need to be increased in order to reduce Johnson-Nyquist noise as well as interference from external sources which low resistance is susceptible to.

3.2. Demodulator Subsystem

3.2.1. Subsystem Introduction

The Demodulator Subsystem plays a crucial role in extracting the transmitted information from the received ultrasonic signals. This subsystem is responsible for reversing the modulation process applied at the transmitter, converting the modulated ultrasonic signals back into their original form for further processing.

3.2.2. Subsystem Details

The circuit that was chosen was a Phase Locked Loop (PLL) which is a feedback system that acts to adjust or lock the phase difference between the output of a voltage-controlled oscillator (VCO) and an input reference signal. Below is the block diagram for this system:

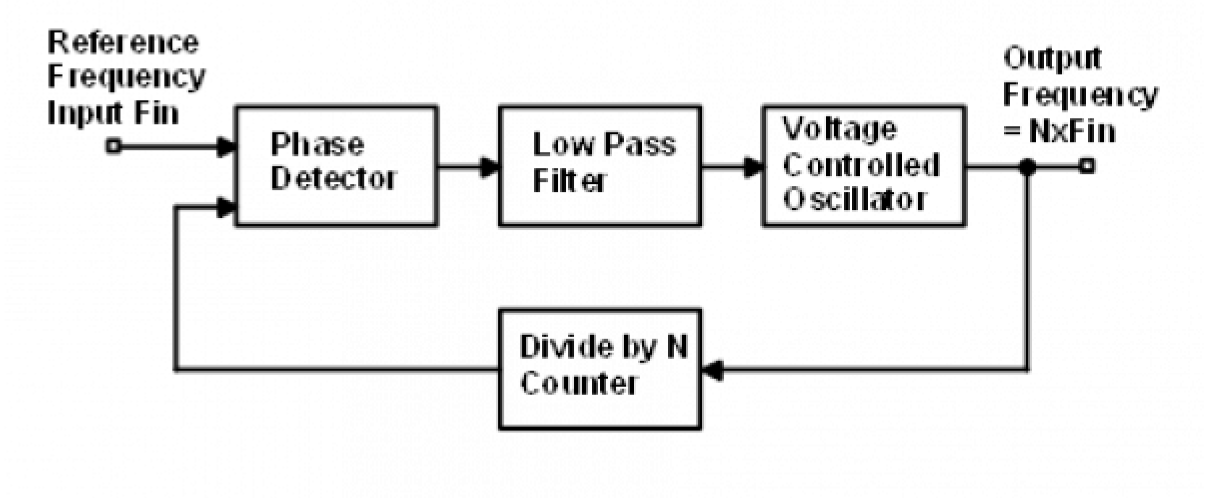

Figure 29: Block Diagram of a Phase Locked Loop

For the VCO, a AD654 was used and configured in the precise way to generate an output signal whose frequency is proportional to the input control voltage. Attached before this was a simple low pass filter that filters out high-frequency components from the output of the phase detector. Finally for the Phase Detector an XOR phase detector configuration was used as it was simple in design which equates to lower manufacturing costs. The schematic of each of these parts is shown below:

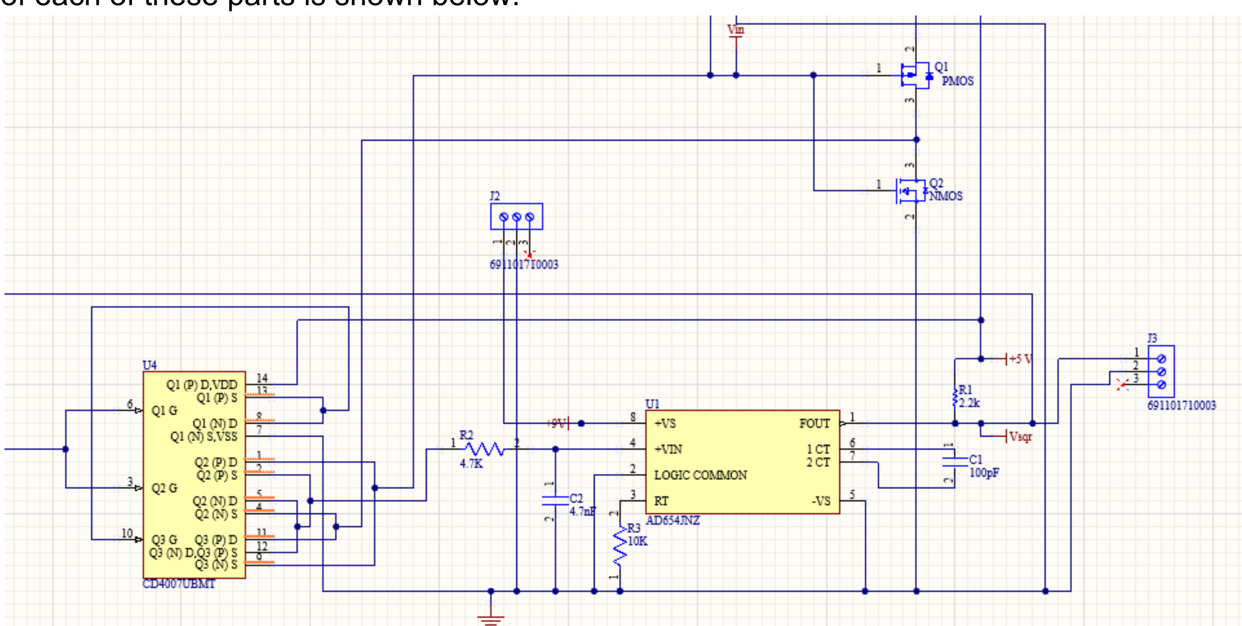

Figure 30: Schematic of Phase Locked Loop Demodulator

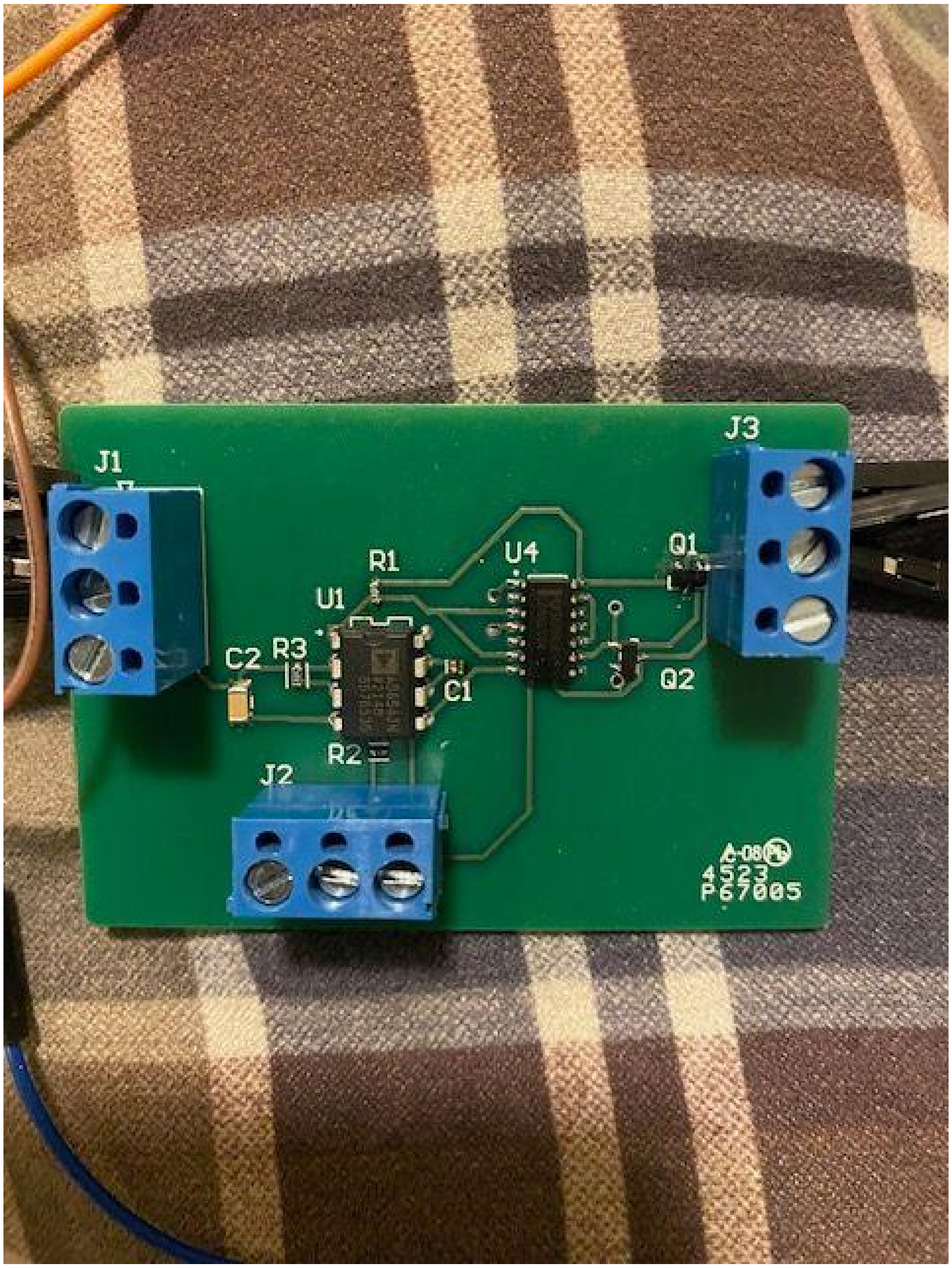

Figure 31: PCB of Phase Locked Loop Demodulator

3.2.3. Subsystem Validation

Just like with the Filter and Amplifier Subsystem, the A2D from Diligent was used as an oscilloscope. This time the Transient Analysis was used as it was necessary to verify the results of the PLL. First, the frequency was set to 250kHz as it is the frequency corresponding to a control voltage of 2.5 V on the VCO. On the transient response we should see that two square saves are stable which means they are properly locked to each other. Vsq should be shifting approximately 90 degrees with respect to the Fref. The filtered output of the XOR phase detector will be at one half of its range. This is roughly 2.5 V when the inputs are 90 degrees apart in the phase. Below is the expected output along with the tested output.

Figure 32: Expected Relation of Fref and Vsqr

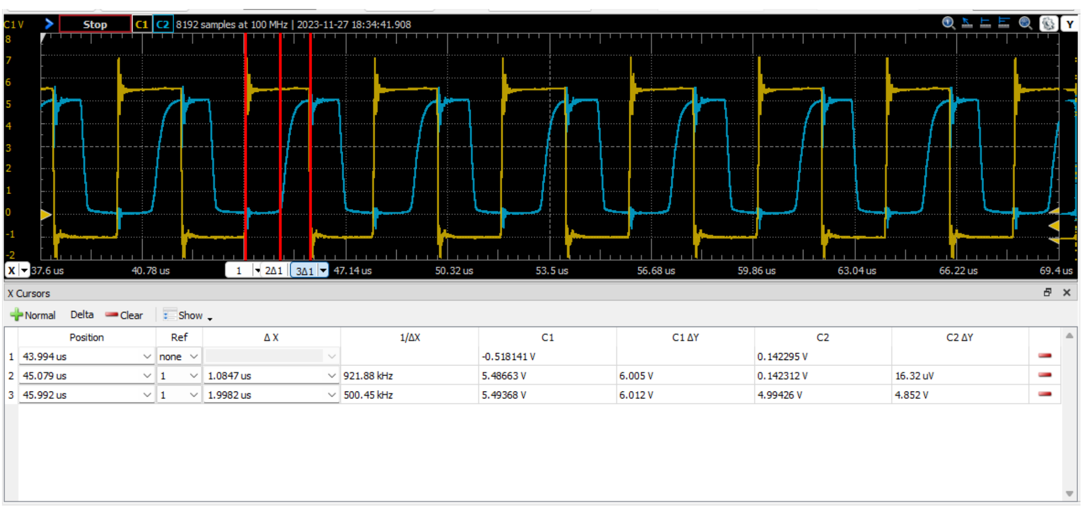

Figure 33: Actual Relation of Fref and Vsqr

When running the calculation on the phase difference between Fref and Vsqr we can see that we get a phase difference of about 94.20 which is overstepping the 90 degrees slightly but this still is a very acceptable result within our bounds.

3.2.4. Subsystem Conclusion

The PLL Demodulator was shown to work as expected. The relationship between Fref and Vsqr was satisfactorily proven to be roughly a 90 degrees phase difference. This should serve its purpose of extracting the information from a carrier wave. The VCO output will become the demodulated signal, free from the carrier frequency but carrying the encoded information from the transmitter.