Multi-Channel High-Gain Low Noise Amplifier for High-Frequency Ultrasound Signal Acquisition

DESIGN DOCUMENT

Team 16
Client: Avishek Das
Advisor: Prof. Manojit Pramanik
Ethan Hulinksy
Ryan Ellerbach
Jonathan Wetenkamp
Yash Gaonkar
sdmay25-16@iastate.edu
https://sdmay25-16.sd.ece.iastate.edu/

Executive Summary

The goal of our project was to develop a way to amplify the signal generated from a photoacoustic tomography (PAT) system, used for research here at Iowa State. This system uses a pulsed laser to induce high ultrasonic vibrations in biological tissue. These ultrasound signals are then measured and used to reconstruct an image of the sample. This technology has been used in research on imaging tumors in mice and other cell cultures. Because of the low amplitude of the signal, it can be difficult to distinguish the signals from noise, so a low noise amplifier, or LNA, is necessary for obtaining high quality signals. Our design requirement goals include low noise, high gain, 8 or 16 channels, a functional bandwidth, small size, and a lower cost than the original system, and the ability to handle the range of inputs that is given from the PAT device. More details on these, and a few other goals/constraints are in section 2.1: Requirements & Constraints.

The client had 2 previous amplifiers that this project was designed to replace. The first of which was an amplifier array that the client had been using that was based off the ZFL-500LN-BNC+ amplifier. This array had three main issues. The first issue was that it was very expensive. The array contained sixteen of these amplifiers, two for each stage, and they cost nearly $140 apiece. The second issue was that the power supply the array used utilized a switching regulator, which created a very noisy ground plane. The third issue was that the amplifier was a low pass filter rather than bandpass, meaning low frequency noise was being transmitted. There were also a few other problems, such as a high-power draw and the large size of the array. The other amplifier that the client had was a prototype for this project. This prototype board fixed a lot of the problems of the first array but had a few problems of its own. The most important problem that this prototype had was that due to its bias voltage, the amplifier could not handle input voltages that were near the maximum that the client required.

We simulated the prototype of the system in NI Multisim and in ADS, trying to implement some changes to solve the issues of the prototype but we did not obtain accurate results because the manufacturer did not supply the SPICE model for the MAR-6SM+ amplifier which was used on the board. Thus, we turned to testing the amplifier manually with an oscilloscope and changing some of the components (mainly capacitors and resistors). After a lot of testing and tweaking, and the introduction of the MAR-3SM+, we got our theory to work and got a frequency response that the client was happy with.

Once our base idea worked, it was time to start implementing that into a new design. We made our PCB schematic and layout on EasyEDA, carefully choosing components and a layout to now take into consideration noise coming from the environment and the other channels. We also designed a new power supply system, using a battery instead of the old one, which caused lots of noise to be introduced into the system. We then ordered, assembled, and tested our first revision board. After testing and then fixing a few mistakes we made when designing this test board, it worked. We then made those changes and made the final board, along with a 3D printed enclosure.

We ran many tests with our client present, and he was extremely pleased with the performance of the amplifier. The system met the requirements for gain, bandwidth, noise, size, number of channels, input range, and cost. Our client told us he plans to use our product after we present it, and it should improve the results of the lab's research. Having higher gain and lower noise will be able to provide much more contrast in the images produced by the PAT system.

Learning Summary

Development Standards & Practices Used

We used standard circuit and hardware practices on this project to prioritize the safety of the group members or longevity of the materials and equipment being used. This includes:

- Turning off power before handling electrical components
- Verifying equipment voltage/current ratings and not exceeding them
- Verifying component power ratings and not exceeding them
- Circuit documentation to avoid mixing up parts
- Connecting circuit to an earth ground to avoid build up on board
- Evaluating solder joints and wires
- Wearing safety glasses when soldering
- Maintaining a safe distance from person soldering
- Letting components cool before handling after soldering
- Blowing emitted particles from solder flux towards vacuum
- Not setting sensitive components on the outside of ESD casings
- Using proper ESD precautions
- Knowing where the eye-washing station and the fire extinguishers are
- Verifying grounding circuit effectiveness

This project did not make extensive use of software, but these are the software practices we did use: Sharing simulation and testing files securely, updating ourselves with current technology and techniques, and saving frequently and with multiple versions in case of system failure.

The engineering standards considered that are applicable to this project are:

- IEEE Std 287-2007: Standard for Precision Coaxial Connectors
- IEEE Std 370-2020: Electrical Characterization of Printed Circuit Board and Related Interconnects
- IEEE Std C63.4-2014: Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment
- ISO/IEC/IEEE 60601-1: Medical Electrical Equipment – General Requirements for Basic Safety and Essential Performance
- IEEE Std 1857.7-2019: Standard for Advanced Audio and Video Coding Techniques for Ultrasonic Imaging Applications
- IEEE Std 1516-2010: Standard for Modeling and Simulation High-Level Architecture

Summary of Requirements

Functional Requirements:

- Gain greater than 30 dB per channel
- Input impedance matched to 50 ohms
- 10 V battery power supply
- Bandpass filtering: 1 MHz-20 MHz
- Output voltage cannot exceed 10 V (Constraint)
- Handling input voltages from 100 μV to 10 mV
- Low noise: Less than 1mV$_{pp}$ when 0V applied

Physical Requirements:

- Protection from Electromagnetic interference
- Small size (~10 inches by ~5 inches) (Constraint)
- Thermal Dissipation
- SMA outputs and inputs

User Experience Requirements:

- Low maintenance
- Easy and intuitive to use
- Long shelf life

Applicable Courses from Iowa State University Curriculum

The courses that we have taken here at Iowa State University that have helped us develop the knowledge needed for this project include:

- EE 201: Electric Circuits
- EE 230: Electronic Circuits and Systems
- EE 330: Integrated Electronics
- EE 311: Electromagnet Fields and Waves
- EE 333: Electronic Systems Design
- EE 414: Microwave Engineering
- ENGL 314: Technical Communications
- EE 435: Analog VLSI Design

New Skills/Knowledge acquired that was not taught in courses

New skills and knowledge that we have learned from this project that we have not learned in class are:

- PCB design and testing
- Surface Mount Device (SMD) Soldering
- Through Hole Technology (THT) Soldering
- Advanced amplifier theory
- RF-Choke theory
- Enclosure material and design
- Power supply design
- EMI with RF signals
- 3D Modeling and Printing

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1. Introduction

1.1. Problem Statement

Photoacoustic Tomography (PAT) is a technology currently in development that can be used to obtain high resolution images of biological tissues. This has many potential applications both in medical practice and research. Professors and postdoctoral researchers at Iowa State University are currently using photoacoustic imaging for research in Iowa State's Microelectronics Research Center (MRC), but their system could be better. One issue encountered by the researchers at Iowa State is that the signals output by their PAT measurement device are too small to be accurately converted by the ADC they are using.

Our project aimed to solve these issues using a Low Noise Amplifier (LNA), which can boost the signal without introducing noise to produce a clear, high-resolution image. Our task is to improve upon the design of the old amplifier to make the signal easier to tell from the noise and boost its strength. Additionally, the current amplifier enclosure takes up a lot of space, is hard to use, and costs a considerable amount. We were tasked to shrink the size of the amplifier array and reduce the cost of system. This is an important issue in the new application of this acoustic imaging system. It is a newer field, and improved image quality can help with determining cell structure and small parts of tissues that were blurry before.

1.2. Intended Users

The Amplifier array that we designed will be used primarily by Iowa State postdoc researchers in the EE/BME fields. It will help them to be able to see smaller variations in output from their photoacoustic imaging setup. Alongside the postdoc researchers, postgraduate researchers and professors will also be using the amplifier. Finally, once research is complete, the lab might commercialize the product so that medical professionals could also use the amplifier.

Postdoc and postgraduate researchers will have almost the same characteristics and needs, although the postdoc researchers will likely have slightly more interaction with the amplifier. These researchers will be Iowa State University students who are doing research using the MRC's photoacoustic imaging setup. While the nature of this research will vary; the amplifier will be used in the same way. The 6 input channels plugged into the photoacoustic outputs and the outputs of the same number of channels plugged into the input of the oscilloscope used to measure. These researchers will want a simple device that requires little to no technical knowledge and can simply be plugged into the system and forgotten about. They also want the amplifier to have enough gain to clearly see all possible information. Their needs are for a modular device that can amplify up to 16 very low voltage inputs to a level of up to 10 volts each while not introducing noise. In accordance with wanting limited interaction with the amplifier, the researchers will also want an amplifier that is small, so that it does not take up additional space in the testing area. These researchers will derive a lot of value from a high-quality amplifier, as it will aid them in their research, and perhaps be able to find things that they could not before.

The professors' interactions with the amplifier will be even more limited. The professors will not want to have to interact with the amplifier in any way and will want to simply have a device that works. Their needs are simply for an amplification device that will allow their research to be completed. While they want to make the student researchers' lives easier, the minutiae of the design falls under the umbrella of the student researchers' needs more than the needs of the research professors. Like the student researchers, the research professors will benefit from this amplifier by having the ability to continue to do the research that they were already engaged in, albeit in a more simple and precise manner.

Medical professionals will be the users who will interact with the amplifier the least. The best-case scenario would be for them to not even know it is separate from the rest of the system. Their needs include functionality and integration with the rest of the system. These medical professionals will not be expected to perform maintenance on the amplifier, so a simplified design is less important than robustness and functionality to them.

Example Users:

Postdoctoral Researcher:

Name: Dr Xavier.

Motivation: Publish high quality research on medical device imaging.

Needs: Not an electrical engineer hence needs a robust system that is easy to use and will not need a lot of time to use it.

Behavior: Balances a lot of projects relies on lab assistants to fix and set up projects.

Feel: Accomplished after using the amplifier to get high quality images due to the amplified signals.

Medical Professional:

Name: Dr York, M.D

Motivation: Use the PAT device to catch and diagnose diseases and use the high contrast imaging the device will produce.

Needs: Limited understanding of the technology hence needs a cheap user-friendly system that will produce high quality and accurate images.

Behavior: Focuses more on the images produced by the device and will try to interact with the device the least.

Feel: Relieved due to catching or diagnosing a disease early with the help of the PAT device.

2. Requirements, Constraints, And Standards

2.1. Requirements & Constraints

Functional Requirements:

- Gain greater than 30 dB per channel
- Input impedance matched to 50 ohms
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Physical Requirements:

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User Experience Requirements:

- Low maintenance
- Easy and intuitive to use
- Long shelf life

This project is primarily intended to be "behind the scenes" and focused on functionality. It achieved this by being simple to install and by not needing to be worked on or fixed often or ever. As far as functionality goes, the device must amplify the input signal without adding in a large amount of noise that will lower the quality of the measurements. This means low noise levels, filtered outputs, and a high gain. The low noise levels were achieved through the design of the amplifier itself, through filtering the outputs, and with the introduction of EM shields. The filtering does most of the work as most of the noise that we expect to see falls outside of the bandpass filter. The high gain is the final requirement and constraint, and the most important one. The project aimed to amplify the output of an acoustic imaging system to a level that can more accurately be recreated by imaging software. Because of this, if the gain is not high enough, the rest of the project is far less important.

2.2. Engineering Standards

Engineering standards are essential because they provide consistency and reliability. Without standards, devices from different manufacturers would be unable to work together, and they may even cause other devices to malfunction or become damaged. Engineering standards allow engineers to know what to expect from existing devices.

IEEE C63.2-2023 - American National Standard for Specifications of Electromagnetic Interference and Field Strength Measuring Instrumentation in the Frequency Range 9 kHz to 40 GHz

This standard is important to our project. The standard is needed for all projects with a detection frequency of 9 KHZ to 40 GHZ. This project falls within these frequencies. As listed above, one of the requirements is ESD shielding that will also fall under the standard of IEEE c63.2-2023.

IEEE 790-1989 - IEEE Guide for Medical Ultrasound Field Parameter Measurements

While this standard does not directly apply to our project, it still holds relevance. This is because this amplifier is primarily going to be used in a medical imaging tool. Even though the amplifier itself does not need to follow the standard the overall imaging device does.

IEEE/AIEE 33-1927 AIEE Standards - Electrical Measuring Instruments

This standard does not have much relevance to the project. This is because while the imaging device that we are building the amplifier for has an oscilloscope, the amplifier does not fall under this category.

These are the standards that were deemed most relevant to our project. However, some alternate standards could be helpful. IEEE 1573-2021 is a standard relating to electronic power subsystems. This amplifier assembly will require a power supply, and this standard could apply to the battery and power delivery subsystem. We designed our amplifier to be compatible with all these standards listed to ensure that we created the best and safest design possible.

3. Project Plan

3.1. Project Management/Tracking Procedures

We adopted a strategy that is a mix of waterfall and agile. The waterfall style makes sense because we have tasks and components of our project that depend on others to be completed before we could move on to the next. The way that the mixture of the two styles comes in is based off the ever-changing next steps. Unlike many projects, the next steps will change based off of the information gathered in the previous one. We selected who does each task depending on who is best suited for which parts are being worked on at the time. Our progress goals are available in our Gantt chart which is accessible to everyone in the project. We also had weekly meetings with our client and biweekly meetings with our advisor. The main problem with the waterfall style of project management is that when one of the tasks stalls the whole project stalls until we can figure out the problem. This proved to be especially troublesome during the testing and design phases of the project, where we had to do iterations of both and yet they both relied on each other.

3.2. Task Decomposition

When we first got the project, our first task was to simulate the amplifier in software like NI-Multisim to make the amplifier work for the application we wanted. The first couple of sims were run to ensure we got an appropriate gain afterward. After getting the results from our sims, we tested the physical prototype to see how accurately the simulations lined up with the real world board, as well as to gather more data that we couldn't reliably get from the simulations.

The next step was designing the boards in EasyEDA. This design was made based on the testing done on the prototype provided to us by the client. The board we designed had 8 channels, and each channel had two stages with the MAR6-SM+ and MAR-3SM+ amplifiers. The need for 2 different amplifiers came from the limitations of the MAR6-SM+ amplifier's output range, as only the MAR-3SM+ could work as the second stage and handle the maximum input requirement without clipping. We didn't use two MAR-3SM+ amplifiers due to the MAR-6SM+ having a high enough output swing to work as a primary stage and it also had other qualities that were more desirable, such as higher gain. This board was later fabricated, and we started testing. To test, we built a few channels and measured the gain and bandwidth. These physical tests revealed that our board did not behave as we expected it to. Through testing we theorized that the primary reason the gain was decreased due to issues with the grounding of the EM shield, which was then creating interference in the channels. The next task was to redesign the boards based on the results we got from physical testing.

The changes to the board include spreading out the stitching vias to create a more continuous power plane, removing the thermal reliefs on the EM shields and on the ground pads of the amplifiers, and adding the circuitry necessary to use a battery or the benchtop supply. We chose a 12V 2400mAh battery and used a linear regulator to reduce it to the 10V needed for the voltage rail. Once we received our order for the new board, we tested it with a few channels, like we did with the first design. Once we had verified that the board worked as expected with a few channels, we used a stencil and a reflow oven to solder the boards. The next task was physical testing with all eight full channels constructed, plus the two partial channels as well. The test measured bandpass, gain, crosstalk, and other noise. A final test was performed by our client, who installed it into his PAT system and tested the resulting output image with and without the board. We finished the project by designing a 3D printed enclosure for the board.

3.3. Project Proposed Milestones, Metrics, and Evaluation Criteria

Milestone 1:
Create a simulation of the prototype amplifier. The simulated circuit should mimic the real prototype's behavior, achieving gain and bandwidth within 10% of measured values. This simulation will allow for easier testing of various component values. With this simulation we will improve the design to meet the specifications of the project.

Milestone 2:
Create a schematic for a new amplifier array that solves the issues of the prototype board. This schematic should in theory meet the main specifications of the project but is intended to be a test board and may not meet some of the smaller requirements, such as a power supply.

Milestone 3:
Create a PCB layout using the newly created schematic. The team will pay attention to routing, grounding, and trace separation for noise-sensitive analog signals.

Milestone 4:
Order and fabrication of the test boards. Once the schematic and layout of the test board is complete the team will have to order the and hand solder the boards.

Milestone 5:
Perform testing on the boards to see if they behave as expected. These preliminary tests should be to measure the gain and the bandpass frequency as well as some tests regarding noise. The new

board will be compared with the prototype board to verify that the changes made have improved the design.

Milestone 6:
Make revisions to the schematic and layout based off the data gathered from the test board. This board should be the final board and therefore needs to include all necessary features for the final project. This milestone also includes the design of the power supply of the board, as well as any necessary circuitry to go with it.

Milestone 7:
Use a stencil and reflow oven to solder all the components on the final board so that testing can be done on every channel.

Milestone 8:
Conduct final bench-top testing on gain and bandwidth, as well as other in-depth tests.

Milestone 9:
Perform testing with the finished design integrated with the PAT system. This will help to show how successful the project was.

3.4. Project Timeline/Schedule

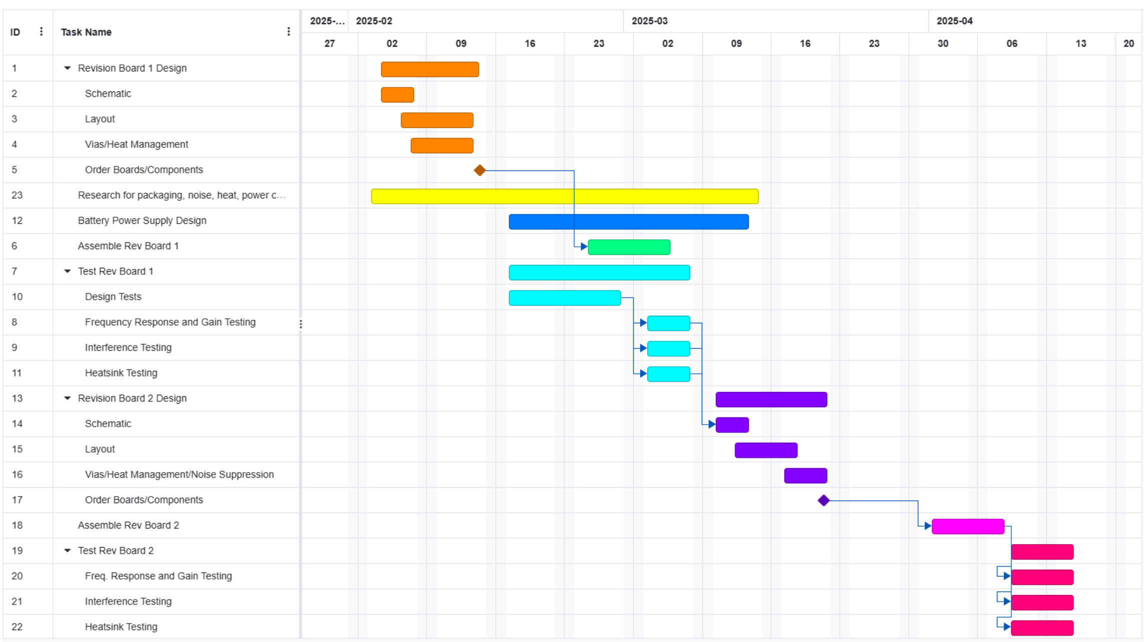


Figure 1 - Gantt Chart

Our project schedule was set up to follow our primarily waterfall style, which is really the only way to go about a project like this. As you can see, pretty much all of the tasks are in series with each other, relying on the previous step to be completed before moving on to that task. The subtasks were made to provide more description and allow for some more detail to be included in the Gantt chart. There are two times where we had to wait for the boards and parts to arrive (they took about a week each time). While waiting, we completed other tasks like planning testing and working on the supporting documentmentation of the project. We ended up being a bit behind due to minor delays. Due to the nature of the project, any delays would delay the entire rest of the project, as there wasn't really ever multiple different tasks being done in parallel. We did, however, budget enough time to finish our design, in specs, before the dates of submission and presentation.

3.5. Risks and Risk Management/Mitigation

Risks for Milestone 1 (Simulation):
Simulation doesn't match real prototype amplifier. This should be mitigated by using the proper spice files and by checking with the measured values. Risk factor: 0.1.

Risks for Milestone 2 (Schematic):
Minimal risks for this milestone. Some small ones could include component choices being out of stock or forgetting to add capacitors on the power supply. These should be avoided by picking common components and having all group members check over the schematic. Risk factor: 0.1.

Risks for Milestone 3 (Layout):
Primary risks for the layout come from bad layout choices. These could be not including ground planes, not using stitching vias, or placing components to close together. We plan to mitigate these by discussing proper layout design with our advisor and also by having him double check the board before purchasing. We will also run DRC checks to verify that we do not break any design rules. Risk factor: 0.25.

Risks for Milestone 4 (Purchasing and Fabrication):
Delays in the arrival of the parts or the boards. This isn't a risk that can be easily addressed, but the team can make sure to give extra time in case of delays. There is also a risk of faulty boards or components being shipped or damaged during assembly. The team will purchase extra boards and components to avoid this possibility. There is also a risk that the team will assemble the boards incorrectly. While this is likely, the team will double check the assembly before applying power in order to avoid any issues this may cause. Risk factor: 0.6.

Risks for Milestone 5 (Testing):
The risks for this milestone are few. The primary one is that the testing is not performed properly. In order to verify that the testing is correct, the team will use the same setup as was used in the testing of the prototype amplifier. If the measured specifications do not meet expectations, the team will know that it is not due to performing testing improperly. Risk factor: 0.2.

Risks for Milestone 6 (Schematic/Layout Revision):
As this revision will be the last one that the team is able to do, this revision will need to be perfect. Due to the small number of changes that will need to be made, the likelihood of something going wrong at this stage is low, however it is costly. Risks should be mitigated in the same method as milestones 2 and 3 and by working with the client to verify that the design is up to their standards. Risk factor: 0.05.

Risks for Milestone 7 (Final Board Assembly):
This milestone has a decent number of risks related to it, but they are all unlikely. The team will use a stencil and reflow oven, which should simplify the assembly process. Additionally, the team

will have already assembled the test board, which should mean that issues with placing components on correctly should be avoided, as the team will be more familiar with the design. The team is not familiar with using Iowa State's reflow oven and will enlist the help of someone who is. Even using a reflow oven, there are still some risks that could prop up, such as tombstoning. These should be avoided through the team looking over the finished boards. Risk factor: 0.1.

Risks for Milestone 8 (Final Testing):
The risks for milestone 8 are small. Due to having already completed the tests twice already, they should work properly. There is a risk associated with the solutions to any problems that the team found in milestone 5 not solving the issue. In order to mitigate this risk, the team will test the solution on the test board if possible. Risk factor: 0.05.

Risks for Milestone 9 (PAT Testing):
Risks for milestone 9 are nearly nonexistent. The team will have already verified functionality through other tests and therefore the board will be expected to work with the PAT device. The only true risk for this milestone is that the project requirements do not properly solve the issues that the client is facing. The client knows what specs he is looking for and this shouldn't be an issue Risk factor: 0.001.

Risks that became issues:

Risk 1. Our risk mitigation strategy of getting the spice files from the manufacturer did not work, as the manufacturer would not provide them to us. We did not expect the manufacturer would withhold these files, and so the strategy failed, and the risk came to be. Additionally, there were not very many similar products on the market, so we could not bypass this issue by using the spice files for a similar product. This delayed the project slightly and meant that any changes to the prototype that we wanted to try out needed to be done on the actual prototype, rather than simulated. This complicated simple things such as swapping out a capacitor, as the old one now had to be desoldered and a new one put in.

Risk 3. We had some issues with our RF shields not being grounded properly due to using thermal reliefs. Thermal reliefs make soldering easier, but they also reduce how much of the pad is connected to the ground plane. There might have also been issues with a lack of stitching vias between the pins of the SMA connectors. While we did our best to follow good layout design practices, we simply did not know that the thermal reliefs would cause issues, or that we needed stitching vias between the SMA pins. While we do not know if it created a problem directly, the power plane was also barely connected in some places due to the stitching vias. This is something that we did not think was an issue, but it may have been.

Risk 4. While the boards did take over a week to arrive, this was accounted for, and other work was done in that time. The larger issue is that the first board that the team assembled was faulty. It is unknown if the board arrived that way or if that was done during assembly. The team's mitigation strategy worked however, and the team was able to assemble a different board and that one worked.

Risk 5. The team ran into a few issues in testing that stemmed from the cables that were used. While the team used the same cables as before, something had gone wrong, and they now only worked at specific angles. This was worked around for a while, until the team could purchase new cables that worked.

Risk 7. There was a component that tombstoned (stood upright instead of flat) on the board and the team did not see it by looking over the board. This was due to the RF shield's crossbar covering up the component. Luckily this didn't cause a major problem as the team was able to fix the error once it was clear that the channel wasn't working.

3.6. Personnel Effort Requirements

Task:	Simulation	Improve Prototype	PCB Design	Fabrication/Testing	Total
Hours:	70	60	40	50	220

Table 1 – Expected Effort Requirements

Task:	Simulation	Test and Improve Prototype	PCB Design	Fabrication/Testing	Total
Hours:	66	68	113	76.5	323.5

Table 2 - Actual Effort Requirements

The effort we expected to put into the project was significantly lower than the effort put into the project. This primarily stemmed from increased hours necessary for the PCB design, with a not insignificant amount of extra time necessary for fabrication and testing. Additionally, the section for "Improve Prototype" was changed to "Test and Improve Prototype" as before we could start improving the prototype we had to do significantly more tests than we expected. This is due to the simulations not being as productive as we had hoped, despite the time sunk into them. The cause of the issues with the simulations is that we were unable to acquire the spice files necessary to properly model the MAR-6SM+ and MAR-3SM+ amplifiers that we used in the design. Had we been able to get these files, the simulation hours likely would have been lower and more helpful than it ended up being, and the time spent testing and improving the prototype would also have been shorter than expected. We underestimated the time PCB design would take because while we had experience in PCB design, we simply didn't expect the complexity of the system. We also ended up using a PCB design software that we were unfamiliar with, which also led to an increased amount of time spent on that section.

3.7. Other Resource Requirements

At the start of the project, we used NI MultiSim and ADS to simulate the performance of the initial design and explore a few changes we had in mind right away to get the desired performance. NI MultiSim and ADS are already available to us through ETG or a university computer. To design the PCB, we used JLCPCB for the design and fabrication of the PCB. To test the PCB, we used the test setup provided to us by our client in the MRC.

4. Design

4.1. Design Context

4.1.1 Broader Context

The amplifier we designed is being used in a large context as a part of a photoacoustic tomography (PAT) device. The amplifier that was developed before this was very expensive, hence one of the main goals was to build a cheaper one that fits this application better. The community we designed for is the medical device industry for research and use in industry. The societal need our design is fulfilling is the need for cheaper and more accurate medical imaging devices. Having cheaper devices can increase the availability and accessibility of this PAT machine, meaning more people can receive help, or more specifically for our user, research can be done for a lower cost. More accurate results from these machines will also help to discern results from the images created.

Area	Description	Examples
Medical Industry	The amplifier is being used as a part of the PAT device. This PAT device will help develop a new medical imaging technology.	The product will help the medical imaging device industry make high contrast pictures quicker
Global, cultural, and social	This project helps in the advancing field of Photoacoustic Tomography. It will be used to achieve better results for a team of researchers already working to research its implementation in healthcare	PAT could be used in the future for imaging of human organs such as the brain. It could be used to find problems such as cancer or other diseases/conditions, earlier.
Environmental	The environmental impacts of the project are minimal. Due to the small number of components and low production quantities the project is not very impactful on the environment. Power consumption has decreased, with the old system drawing 14.4W, while the new one uses 4.5W on the benchtop supply and 5.4W using the rechargeable battery.	Resource production for raw and processed materials such as silicon or ICs will not be impacted by the small number of components that would be used, even if there were many units produced. The power used is minor, but a decrease in power is still beneficial to the environment.
Economic	The newly designed board costs $141.49 each, without a battery, and $164.48 with a battery. This is comparatively much less than the original setup which cost $139.50 per channel, for a total cost over $1116.	While the savings are high on a per board basis, cost savings will be comparatively low due to a need for only a small number of systems.

Table 3 - Broader Context

4.1.2 Prior Work/Solutions

The client had an existing amplifier that worked, however there were some issues with it, including electronic noise, cost, and size. This amplifier array was built using the ZFL-500LN+ amplifier from mini-circuits. The client began work on a solution, creating a single channel prototype board that he based off the ZFL-500LN+ in the previous array. The prototype was just a single channel and was unable to handle the input voltages required. The prototype also had no RF shielding, no power supply, and a few other issues. There was also very little documentation on the previous work, which meant that before we could really start working on our own design, we had to do a lot of work testing and understanding the previous design.

4.1.3 Technical Complexity

Our project includes many factors that contribute to the complexity of its design. First, we need to consider many different parameters which characterize the performance of our amplifier: gain, bandwidth, power supply, noise levels, distortion, and other factors.

The project also includes in-depth knowledge about PCB design. One scientific principle that we used was in calculating the ideal trace width to keep impedance between components negligible. This application follows the transmission line theory of impedance of a signal traveling along a narrow conductive path. Keeping this parasitic impedance low was imperative to keep the performance of certain components in their ideal operating ranges. For example, the pass band of our filter is dependent on a term that is proportional to the product of the capacitance and impedance shown at the output of the amplifiers. Any parasitics present can introduce ringing, peaking, and nonlinearity in the signal. Also, for RF signals and our SMA connectors, 50 Ohm impedance matching between parts of the circuit is critical to avoid attenuation in the signal.

Knowledge of SMD components such as the difference between linear and switching regulators were paramount to the design of the power supply system and therefore the overall functioning of the device. We learned that switching power supplies introduce too much noise for low amplitude RF signals such as ours. After testing with a switching power supply and a linear power supply, we could see that the clock inside of the switching power supply provided high frequency noise, which would interfere with our signal.

In depth knowledge of crosstalk, electromagnetic interference, and how to avoid it in PCB design as well as in the enclosure and usage of the board is also necessary to reduce noise levels as much as possible. We completed research and testing with EMI/RF shields around each channel of our amplifier to protect each channel from projecting electromagnetic emissions onto each other. We also played with the idea of an enclosure around the entire system, towards the start of the design process, to keep away noise from the environment, but later thought it not necessary if we shielded each channel individually. This is something the team had not had much prior exposure to and was something we had to learn through research as well as testing in the lab.

Another subsystem that required extensive thought and theory is the grounding of our board. Normally, wide ground traces and maybe even ground via stitching across a ground plane can suffice for your PCB. But for our PCB we realized, especially with the shields, how important and how nuanced grounding a design can be. After taking generous consideration for the grounding and after testing on our first board, we can safely say we did not ground the RF shields on the test board correctly or enough to meet the performance desired. We thought and discussed how to better take care of this issue and came up with a few solutions. First, we removed the thermal reliefs from the shields to the ground plane. Typically, thermal reliefs are used to make soldering easier, but in this case, they hindered how effectively the RF shields were grounded. This ensured that our shields were properly tethered to the same ground net as the rest of the board and were no longer pieces of metal at a floating voltage that can pick up noise from the surrounding environment. Secondly, we added copper pours around the ground pads of the amplifiers and added more vias near them, because their performance is what's most important to the output's performance. Thirdly, we added more vias and copper pours around the GND pads of the SMA connectors, which affect how well the signal is measured and transmitted to and from the board. All these changes we had to make show how this project has added depth and complexity to a topic that we had learned before when creating PCBS in the past.

The requirements and scope of our project provided the opportunity for us to learn many challenging theories and ideas that are important in the field of RF and analog amplification and PCB/circuit design. While others may be able to design similar systems on the market, ours combines many favorable qualities and features into a unique solution for our unique application and user needs.

4.2. Design Exploration

4.2.1 Design Decisions

One design decision we had to make was determining our supply voltage and bias network. The limit we have for the amplifiers' output voltage is 10V, but our design was supposed to have a 5V supply based on the original specifications. The problem with this is that the amplifier we use is biased, so if we want a high enough gain without clipping, the output voltage must go up to 7V. Therefore, we had to make a design decision on whether to increase our supply voltage or accept a reduction in gain due to clipping. We decided to switch to a 10V power supply, as our client desired a high gain, and the 5V supply was not as high of a priority for them.

Another design decision we made was to make our layout on the PCB linear. For example, the first amplification stage is on the left, and then they cascade to the right. The primary purpose is minimizing the lengths of our traces to prevent interference and parasitic impedances. This layout also allowed us to isolate each channel from the others to add shielding around each channel, helping with our noise constraint. A final bonus of this design is ease of understanding. This design looks lined up and clean on the PCB. This blueprint makes it much easier for users to be able to see what the circuit is meant to do and be able to change out components quickly and easily without mix-ups.

Another decision we made was to shield each channel and not the entire system. This makes sense in order to both reduce crosstalk between the channels and block them all from environmental noise coming from outside the system. This was one of our essential goals to increase the signal to noise ratio to increase the contrast and accuracy of the images generated by the PAT technology.

We decided to have two ways to power the amplifier array. There is a terminal block that can be used in conjunction with a benchtop power supply at 10V and a barrel jack that a 12V battery can be plugged into. The decision to have both came from both options being useful to the client. A battery offers the lowest noise possible, but must be recharged somewhat frequently, as it has a battery life of about 5 hours. The benchtop supply is something that the client will have access to and will not need to be recharged.

4.2.2 Ideation

One thing that we had to choose carefully while planning the initial design was determining which amplifier we would use. We examined and researched many different amplifiers. While our client suggested an amplifier, we made sure to research other options to be sure that what he suggested would be best for his application.

One option we considered was a nonspecific multipurpose op-amp. We could design the resistor network to reach a gain that we desired. There are two main issues with this idea, the first being that to reach the gain and bandwidth necessary the gain bandwidth product for the op-amp would have to be very high. The other issue is that in order to set the gain we would have to use a resistor, which would create noise. These two issues meant that this solution was not feasible.

We then agreed that the best solution was to use the MAR-6SM+ that the client suggested. However, this amplifier didn't have a high enough gain on its own. We therefore looked into using multiple stages, which is what was done on the prototype board. In order to use multiple stages, we needed to use a different amplifier for the second stage, as the MAR-6SM+ did not have the output voltage range necessary. We therefore looked into other options and decided to use the MAR-3SM+ for the second stage, as it is from the same family of amplifiers. It offers a higher output swing at the cost of a lower gain.

We also looked into adding a third stage to the design, another MAR-6SM+. As long as we didn't place this amplifier at the end of the system, the output swing issues shouldn't matter. We decided not to add a third stage to our design, as the gain didn't need to be increased at the moment. We still left the door open for the client to create a new revision of our PCB that would include a third stage. Additionally, we added 2 partial stages to our design, one with the MAR-6SM+ and one with the MAR-3SM+. This allows the client to tune the gain to his liking, as well as test out how the board would work with a third stage. One final thing to note is that the output and inputs use the same connectors, meaning that the output of one channel can easily be connected to the input of another, effectively making a 4-stage amplifier, if the client so desires.

4.2.3 Decision-Making and Trade-Off

We considered the many options available when selecting our amplifier and the number of stages. This mostly started with comparing the data sheets of the different possible options. Using data sheets, we could easily compare operating frequencies and gain. We also compared the footprints of each of our possibilities. We decided the most accessible and straightforward option would be to use the multi-stage amplifier.

One trade-off we had to make was when we decided to use 10V instead of 5V as the supply voltage. This gave us more headroom in terms of signal swing but was suboptimal in terms of being close to the voltage limit that the computer used for processing can handle. In the end we decided (with input from the client/user) that the right methods will be used to make sure that this downside is not an issue, and we went ahead with using a 10V rail for the biasing of our amplifiers.

Another design decision we made that has a trade-off is deciding to go with one board that has 8 channels all on the same board instead of 8 individual boards. One board gives us an easier time manufacturing the system, an easier time routing power to all the channels, allows us to keep every channel referenced to the same ground net easily, and reduces cost spent on the PCB itself, as well as saving a few components (power connection to board, bypass capacitors, and linear regulator system for the battery we chose). The downside would be that the system is less modular, with it now being more difficult to interchange one channel or edit components of a single channel. While modularity, was an emphasis in the original requirements, our client has agreed that our solution will work better and the ability to take one channel out and play with it, shouldn't be needed.

More discussion on decision making and trade-offs can be found in section 4.4 Technology Considerations.

4.3. Final Design

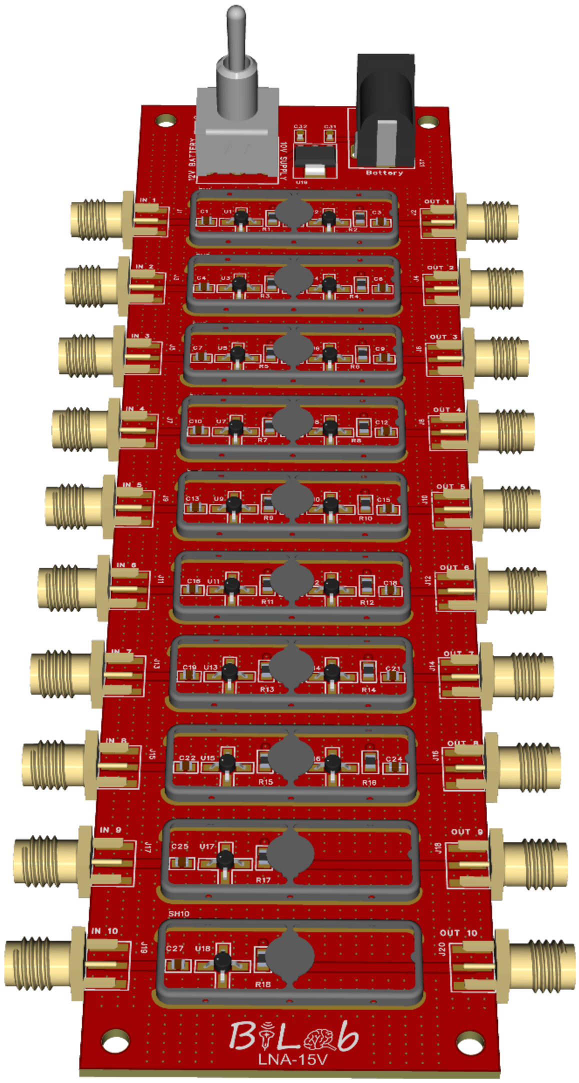


Figure 2 - Full 3D Model of Final Design

4.3.1. Overview

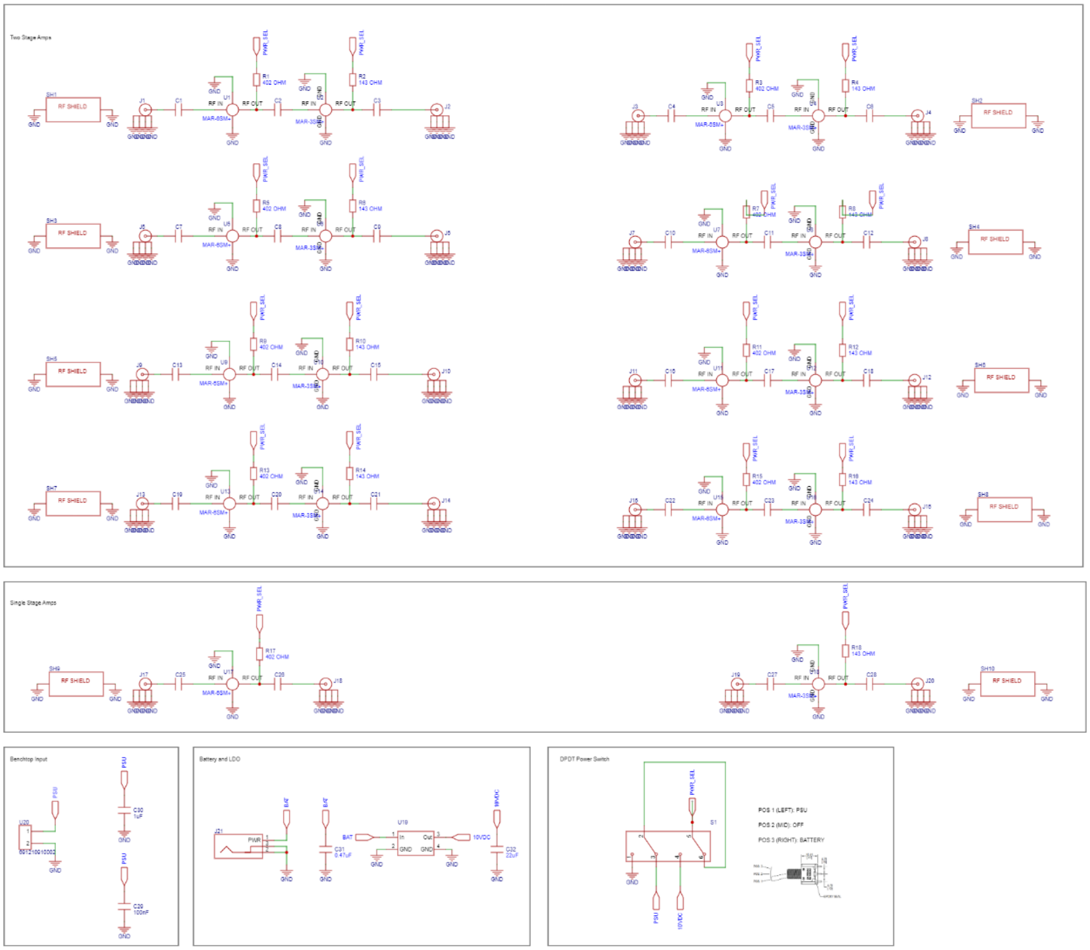


Figure 3 - Final Design Schematic

The problem is that the quality of the imaging software for receiving ultrasound signals is currently lower than our client would like. Our solution is an eight-channel amplifier to boost signal strength. The number amplifier boasts two stages but can be chained from one channel into another to increase the gain. Additionally, the stages in each are implemented slightly differently, with the last stage using the MAR-3SM+ amplifier and the first stage using the MAR-6SM+ amplifier. The two stages using different components comes from the tradeoff between gain and maximum output. The MAR-3SM+ amplifier doesn't have as high of a gain as the MAR-6SM+, but the MAR-6SM+ is unable to reach the voltage levels necessary at the output. There are also 2 atypical channels that are different from the eight main channels. One of these channels is built with just an MAR-3SM+ while the other has just an MAR-6SM+. The purpose of these channels is to allow the user to modify the gain they need. We have designed the board to the specifications we were given but are aware that our client's needs may change in the future, which is why these extra channels are added. While the user won't be able to increase the gain of every channel, if they find that they need to, it would be simple for the client to create a new version of the design that has three stages on each channel instead of two.

4.3.2. Detailed Design and Visual(s)

The schematic of a single channel is shown below in Figure 4 – Single Channel Schematic. J3 and J4 are the SMA connectors by which the signal will be routed in and out. The signal first travels through C4, the first DC blocking capacitor, and then into the first amplifier stage. This amplifier is an MAR-6SM+ and has the higher gain of the two amplifiers. It is grounded on both sides and is biased by a DC current at its output by the DC voltage PWR_SEL and the R3 resistor. The signal then travels through C5, the second blocking capacitor, into the second stage, utilizing the lower gain MAR-3SM+. This lower gain amplifier is necessary due to the MAR-6SM+ being unable to handle the output voltage that is required with a 10mVpp input, which is the maximum voltage that the system needs to be able to be used with. The MAR-3SM+ has a higher operating voltage than the MAR-6SM+, which allows the voltage swing to be higher, and therefore allows the system to properly amplify the 10mV input signal. This amplifier is bias like the first, with the same voltage supply rail and R4. The resistance here is different from the first due to the amplifier's higher operating voltage. The signal then goes through a third blocking capacitor and into the output SMA connector. Off to the side of the schematic is the RF Shield. The RF shield is placed over all these components in the layout and should protect them from EM noise.

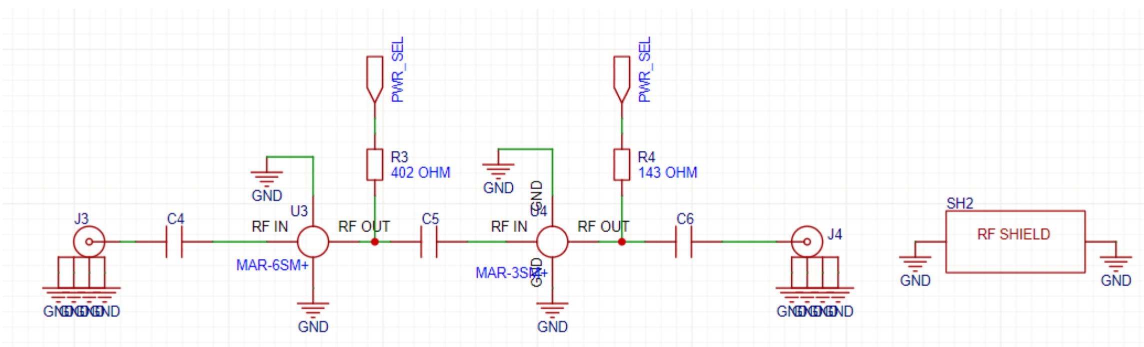


Figure 4 – Single Channel Schematic

4.3.3. Functionality

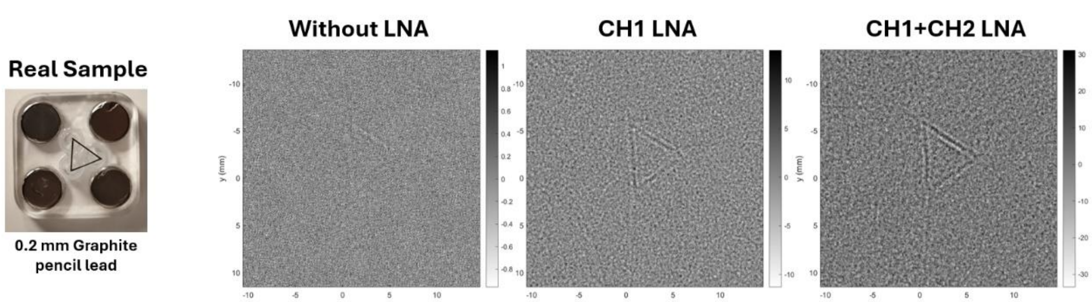


Figure 5 - Amplifier in use with PAT setup

In Figure 5 - Amplifier in use with PAT setup, it can be observed that a single channel of the amplifier makes triangular sample much clearer than without the amplifier. A test was also performed using two channels of the amplifier, allowing for the image to be even clearer. This proves that the amplifier works. In terms of user interaction, it is minimal and easy. The user connects the SMA connector from the scanner into the amplifier's input instead of the computer, then takes another SMA connector and connects the amplifier's output to the computer.

4.3.4 Areas of Challenge

There were a number of challenges in this project. The main issue we had early on was that there was not a well-defined scope. This doesn't mean that the scope was always increasing, but rather that we did not know what goals we had to meet, or even what point we were starting from. Once this was figured out the project became significantly easier. We ran into a few more issues, such as problems with being unable to simulate the system in the way we wanted, or with the real world not matching the theoretical. The most important example of this is with the grounding of the RF shields, which were effectively at a floating voltage due to the thermal reliefs not adequately grounding such a large component.

4.4. Technology Considerations

The distinct technologies that we used in our design are SMA connectors, EM shielding, LDO regulator, a multistage amplification structure, and FR-4 substrate material for the PCB.

We chose to use SMA coaxial connectors to interface our RF signals. They are excellent at high frequencies and easy to impedance match, which is important in minimizing signal reflection and loss. The trade-off would be a higher cost than other methods of connection.

Electromagnetic shields are something we chose to implement to protect each channel from environmental noise and the interference coming off the other channels. The negatives of adding these is an increase in cost, weight, and the fact that they cover the circuit, making it hard to see what's inside and harder to debug an issue.

The battery power supply was a big thing we needed to add because the of the noise from the old switching power supply. This requires a low dropout regulator or LDO to stabilize the voltage from the battery. LDOs are linear meaning a very low noise, which is ideal for our RF signals. They are cheap and extremely easy to implement, and we have experience designing those. The weakness is power efficiency, as there needs to be about 2V*465mA = about 0.9W burned off from the 12V battery to drop to 10V supply.

Lastly, we used a multistage amplifier architecture which is two stages of amplification cascaded. This allows for a tailored frequency response and impedance matching per stage with were extremely important to us. This also allows for a high linearity which is essential when the input signal magnitude changes. It makes sense for our application because we only ever go to three stages of amplification, so it never gets too complex.

5. Testing

5.1 Unit Testing

A single stage of our amplifier board was the device under test. The most important test for our project was the frequency response, where gain was measured across a large range of frequencies to determine the bandwidth and gain of the amplifier. This was done using 3 main tools, a signal generator, an oscilloscope, and a computer running LabVIEW. LabVIEW utilized code that would sweep through a range of frequencies and send them, along with an input voltage, to the function generator and to channel one of the oscilloscopes. This generator was then connected via SMA to the board, where the signal would be amplified and then ran through another SMA connector to be sent to the second channel of the oscilloscope. LabVIEW would then take the information from the oscilloscope and plot gain in volts per volt against frequency. The other tests that we ran were transient tests, noise tests, and linearity tests, which were all done similarly to the frequency response, using LabVIEW. Thermal emission tests were done by using an IR no-contact thermometer.

5.2 Interface Testing

The different interfaces of our design are the 10 channels of the board, the power supply circuit, the grounding network, and the SMA connectors and cables which connect to the PAT device or the oscilloscope for testing. To test many of these, they had to be used together. For example, the grounding network needs something to ground, so it's tested in juncture with a channel of the amplifier. To do this we can hook them up also with the power supply and see if there's any voltage or noise in the ground net, not being swallowed up by the ground plane. To test the power supply to board connection we hook them up, grounding being ever-present, and measure the voltages with a multimeter or oscilloscope at the connection with the board and the biasing points of the amplifier to make sure the right voltage levels are being presented. We also conducted crosstalk tests to see how each channel interacted with each other, as this was a big concern for the user.

5.3 Integration Testing

Nearly the entire system is part of the critical path. While each channel is not critical for the functionality of the other modules, the intended implementation of the device will use all channels in parallel. The only parallelism other than the channels is that we have two options for a power supply. A single channel of the device could fail without affecting the other channels, however this will cause the overall system to not work as intended, as the users would like to be able to use all 8 channels of the device. We decided to keep the old reliable way of powering the boards available in case the battery dies, or they are waiting for a new battery, etc. The power supply and grounding circuits are critical, as if it doesn't function properly, none of the channels will be able to function properly. This was something that we experienced when testing our first revision board. Our grounding network wasn't working as well as it should, and it made it difficult to obtain any data on the amplifier's functionality. We did, however, figure out a work around to see if they rest of the board worked, before going to design the final revision. The enclosure is not critical, as it will only serve to hold the board in place.

5.4 System Testing

To test the user requirements the whole amplifier system (not the PAT device) need to be included. Since our unit that we tested was a single stage, we had to hook that up to the power supply, grounding network, and oscilloscope (testing device) to be able to test the system. We experienced issues with the testing setup throughout the first semester and the start of the second semester but eventually figured out why it wasn't working all the time. There were two main reasons the test setup didn't work, the first being that the oscilloscope we used was not matched to 50 ohms. This is an issue for just the test setup as the ADC that the final device will feed into is properly matched. The second issue is that we were using old cables that did not work well and when we bought new ones the testing setup worked perfectly. We used the different pieces of our system together to test each part of the device. This was something we had to do essentially the entire time, because each piece depends on the others. We also had to test each channel individually to verify that channels one through eight all performed the same and that channels nine and ten also performed as expected.

5.5 Regression Testing

The new additions to the device that we implemented are the battery power supply, the EM shields, having all the channels on one board, and the enclosure. The battery power supply was easily able to be tested by measuring voltages coming into the amplification stages. Making an LDO circuit to channel the battery supply to 10V from 12V was also something that three of us had experience with in the past and we were not worried about that messing up functionality. The EM shields were something that we hadn't had any prior experience with before and there was a little learning curve that had to be overcome with those. That's why we made a first revision board, tested it, and made the fixes needed to the final design.

5.6 Acceptance Testing

To determine if our board met the specifications given to us by the user, we ran six different tests with our completed board. The requirements we tested for are gain and bandwidth, signal integrity, noise levels, crosstalk levels, power consumption, and linearity. Our client/user was present while we ran the tests and was able to give us immediate feedback and input on which tests were important to make sure were included.

For measuring gain and bandwidth we ran a frequency response and plotted the results using LabVIEW, which ran through different frequencies, plotting the gain at that frequency. Then gives us the gain at the passband and we can find the bandwidth by using the −3dB definition of bandwidth, looking for where the signal magnitude drops to −3dB from the passband gain.

To ensure signal integrity was kept we ran a transient analysis to look at the input and output waveforms. We did this on both the oscilloscope and the LabVIEW displays. Good signal integrity means that the output waveform matches the input waveform in terms of shape with no clipping, spiking, or distortion.

To measure noise and crosstalk levels we were able to again use a transient analysis on LabVIEW. We set the input to zero and observed the output. We plotted this for the benchtop power supply and the battery power supply. We also tested crosstalk by again setting the input to zero, but this time attaching the output of one channel and feeding it to the input of a nearby channel. This gives us the noise caused by crosstalk between the two channels. We measured and compared crosstalk noise with and without the EM shields to find out if these were necessary.

5.7 User Testing

Throughout the whole design, we thought about accessibility for the user. We worked very closely with the client for the project who will be the main user of the product. We added a few tests for things that we thought would be important for the user: Linearity and thermal emission. Linearity wasn't a design constraint but is something that is implied when dealing with amplifiers. Thermal emission and how we distribute the heat from the board is also something that must be thought about whenever using high power systems. As far as accessibility, we worked with our client, asking his opinion on how he would like things to connect at the top level, and what controls would be easiest for their setup. For example, he helped us decide on the metal DPDT switch that controls which power supply is to be used.

5.8 Other Types of Testing

One additional type of test we ran, that made sure our board was usable but wasn't explicitly stated in the design requirements was thermal testing. This is important to test to make sure our board didn't generate too much heat that might make components break down, stop working correctly, or start a safety hazard. To test this, we used a no-contact IR thermometer which is basically a thermal radar gun. We operated the device under normal operating conditions and then measured the temperature at different points across the board.

Power consumption was something that wasn't a constraint but is always something to think about when designing electrical systems. It can affect the thermal dissipation systems needed for the design and the electric bill of the user. Power consumption tests were run by measuring the current drawn and the bias/supply voltage. Power is current times voltage and there shouldn't be any surprises in this test.

5.9 Results

We measured an average gain of 32.7dB for channels 1-8 of the board (two stages channels). The average gain was 21.8dB and 12.5dB for channels 9 and 10 respectfully. The bandwidth was about 1.1 to 24.2 MHz for each channel. Our client was extremely happy about the gain as even with only the two stages, it was above the specified 30dB. For frequency, the client was satisfied with that too because the specification for bandwidth varied. He shouldn't be needing anything above around 10 MHz at the moment, but higher frequency signals may be required in the future.

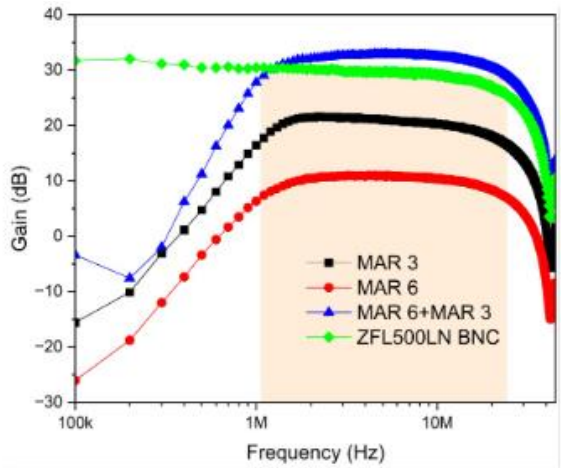


Figure 6 – Frequency Response of the Different Channels and Comparable ZFL500LN BNC

For signal integrity we observed an output signal that mirrored the input signal perfectly up to the detection of our instruments and the level accepted for the application. There was no clipping, spiking, or distortion of the test input sinusoid, appearing on the output. Our client was pleased with the quality of the waveform.

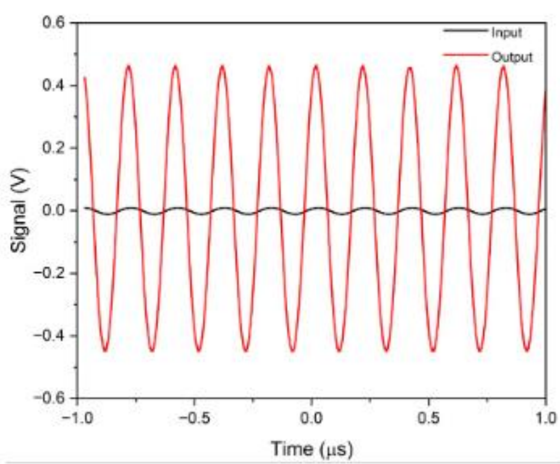


Figure 7 – Output vs Input Transient Waveform

For noise testing we put nothing at the input and got an output noise level that went from about –0.47mV to 0.17mV or 0.64mV$_{pp}$ for the benchtop supply and an output noise level that went from about –0.33mV to 0.08mV or 0.41mV$_{pp}$ for the battery supply. These are well under our noise spec of 1 mV$_{pp}$, which the client was very happy about.

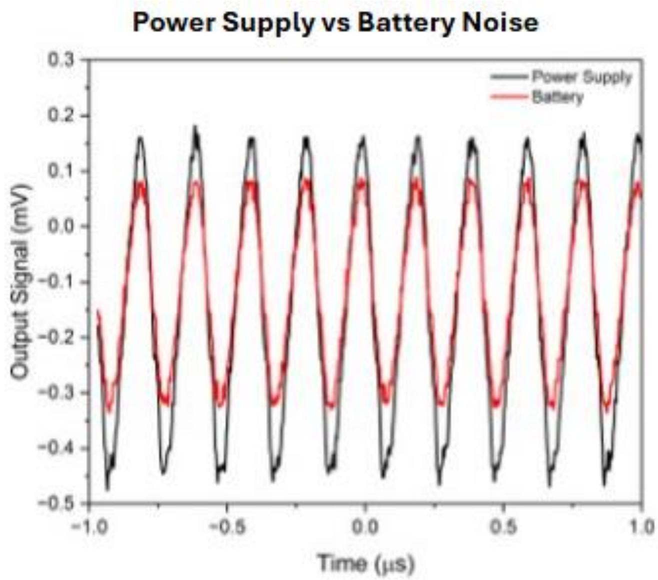


Figure 8 – Benchtop Supply vs Battery Noise8

Crosstalk testing was similar to the noise testing previous, but slightly different. We input a 10mV signal into channel one and then measured the output of channel two. This allowed us to see the crosstalk noise between channels. We measured this both with and without the EM shields to see if they improved crosstalk. Crosstalk is not the primary use of the shields, however we expected that it would be a nice side effect. We can see that the crosstalk without them goes from about -0.47mV to 0.21mV or 0.68mVpp. With the shields, the crosstalk noise goes from about –0.46mV to 0.17mV or 0.63mVpp. This might not seem significant but is over a 7% reduction in crosstalk between channels, which might make a difference in image detection.

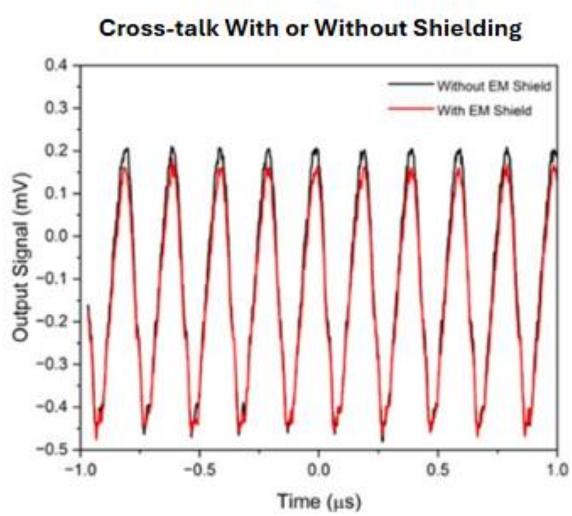


Figure 9 - Crosstalk With vs Without RF Shield

Power consumption tests went as expected with the amplifiers not being activated until they received the proper biasing current which is controlled by the voltage provided which will normally be 10V. Power consumption at 10V proved to be 4.65W, which was not a requirement, but our client said was acceptable.

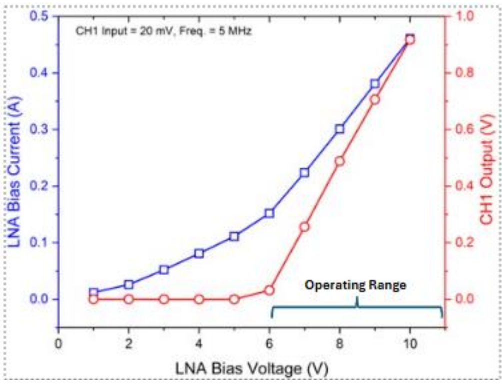


Figure 10 - Power Consumption Based Off Bias Current and Voltage

Temperature tests went as follows: The maximum temperature we saw was just less than 40°C, which is warm but expected when we are running 4.65 W of power through the board. The temperature-limiting components are the amplifiers MAR-3sm+ and MAR-6sm+, and the DPDT switch. The MAR family of amplifiers are functional up to 85°C, making 40°C not an issue at all. From the data sheets we expect that if heating were an issue the amplifiers would be the first to go, so it is good that we did not see temperatures close to their maximum. We were unable to test the temperature of the device in the enclosure, however if the client finds the enclosure is a problem the top could be removed, or a fan could be added.

We did 2 main AC sweeps, one with channel one fed into channel two, and one with just channel one. The reason we tested cascading the channels together was that we expect our client to need higher gain in the future, which could be done in this way. We tested a single channel as that is the primary way that the current system is intended to be used. We also tested the old amplifier array and found that our new design had a slightly higher gain, low frequency noise filtering that wasn't present on the design being replaced, and a similar cutoff frequency on the high end. This should make our board a more effective amplifier than the original, with the added benefit of being significantly cheaper and smaller.

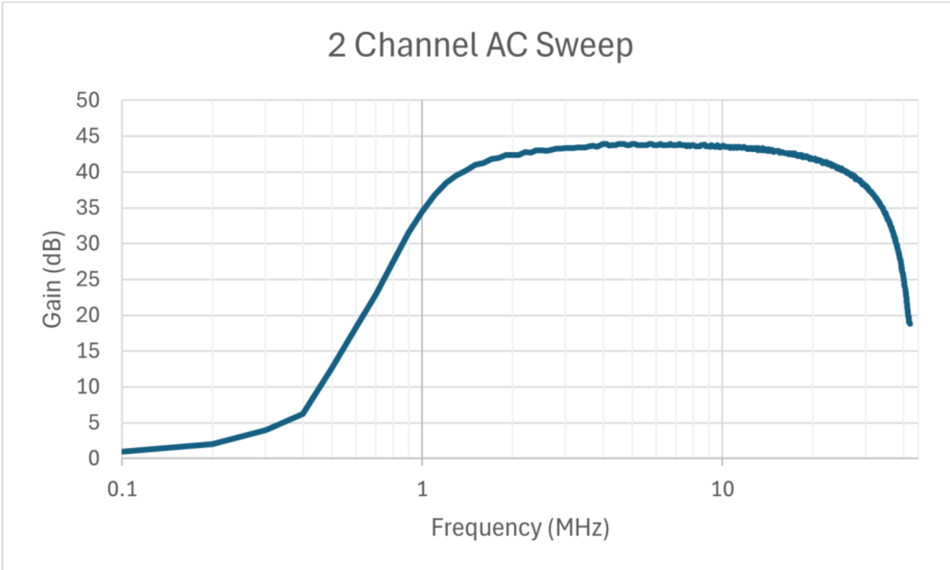


Figure 11 - Final Board AC Sweep with Channel 1 output fed into Channel 2 input

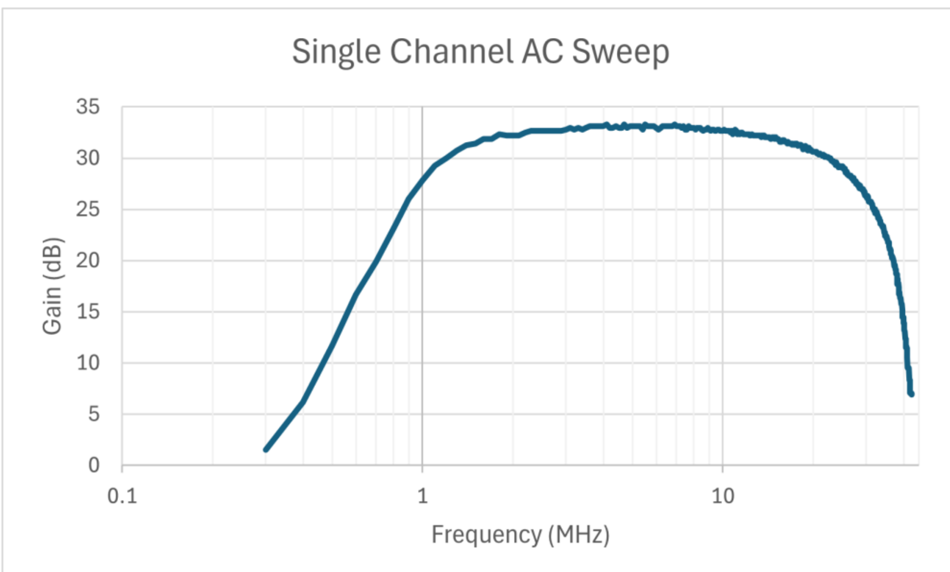


Figure 12 - Final Board AC Sweep of Channel 1

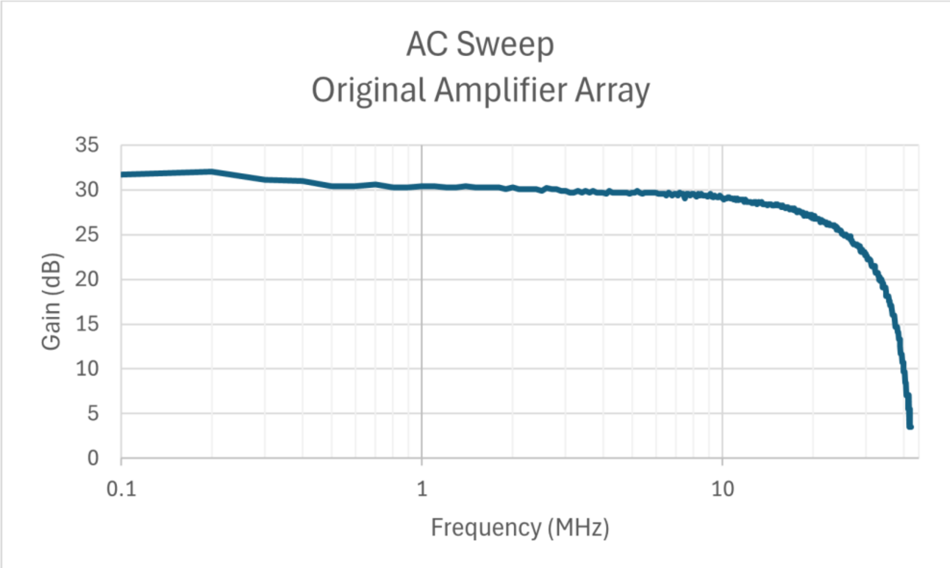


Figure 13 - AC Sweep of the Amplifier Array that's Being Replaced

We also tested the noise in the power supply of the original array, which used a switching regulator. It's clear to see from this graph that there is switching noise in the power plane. The noise peaks as high as 2mV_{pp}, a significant amount of noise compared to the maximum input voltage of 10mV_{pp}. By using a battery this noise disappears.

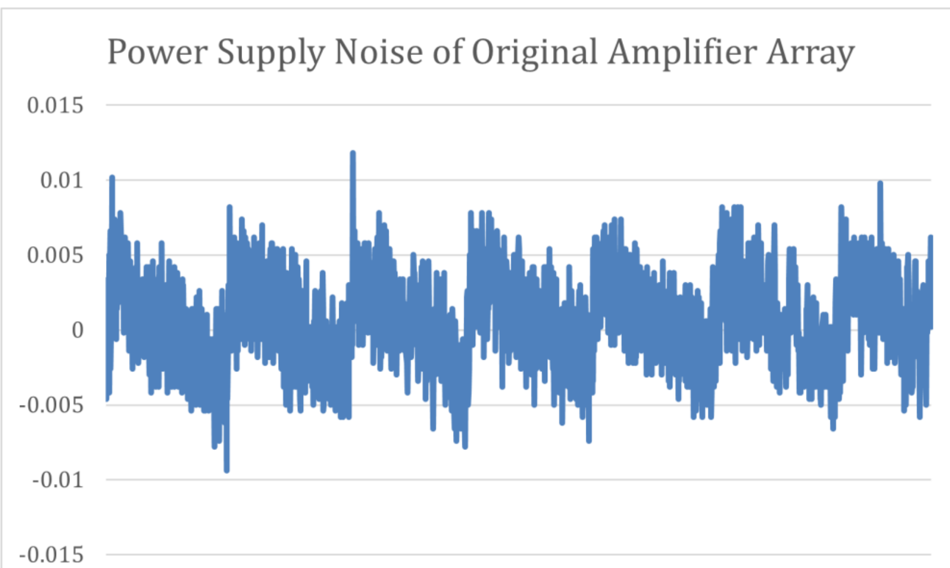


Figure 14 - Power Supply Noise of the Amplifier that's being Replaced

6. Implementation

To implement the amplifier with the PAT device the team designed an enclosure and a power supply. We created two options to power the amplifier, with either a benchtop 10V supply or a 12V, 2400mAh battery. The battery is dropped down to the 10V that we use to bias our amplifiers through a linear regulator. A linear regulator was chosen over a switching regulator despite a lower power efficiency to decrease noise in the power plane. The design that this amplifier is replacing used a switching regulator for its power supply, which caused the switching noise in the system to overwhelm the input signals. The amplifier draws approximately 465mA of current. When the amplifier is connected using a benchtop supply this corresponds to a power dissipation of 4.65W, and when connected to the battery draws 5.4W. This means that the amplifier can be run off a fully charged battery for more than 5 hours, which is sufficient for the users of the PAT device.

6.1 Design Analysis

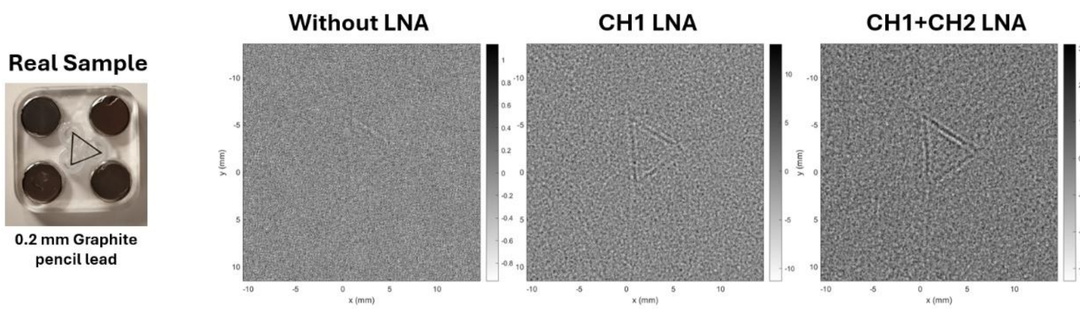


Figure 5 - Amplifier in use with PAT setup

The amplifier works in the PAT setup. As discussed earlier, the triangular sample is much clearer the higher that gain of the amplifier. It should also be noted that the maximum and minimum values (labeled on the side of the images) increase greatly, showing that the amplifier is creating a greater variation between the background and the sample. The amplifier improves the system by feeding a higher amplitude signal into the ADC, effectively increasing the resolution of the ADC and therefore the clarity of the image. We expected the cascaded channels to have more of an effect on the results than this image shows, but it is still an improvement over one channel.

7. Ethics and Professional Responsibility

Our ethical and professional responsibilities in this project are grounded in our commitment to ensuring quality and integrity in everything we do. We prioritized human well-being and safety, sustainability, honesty, competence, and social responsibility in our simulations, design, development, testing, and fabrication of our product.

7.1 Areas of Professional Responsibility/Codes of Ethics

Area of Responsibility	Definition	ACM Principle	Our Team's Interaction

Work Competence	Completing work with high efficiency and quality, progressing towards the goal.	2.1 Strive to achieve high quality in both the processes and products of professional work. 2.6 Perform work only in areas of competence.	Splitting up work to each member that knew the most about that subject. If nobody knew enough, we researched the topic to not be going in blind.
Financial Responsibility	Being transparent about financial budgets, risks, gains, loses, and economic impact.	1.3 Be honest and trustworthy	We all discussed the financial impact of decisions as a part of determining the best outcome. For example, during component selection and circuit design.
Communication Honesty	Being truthful and transparent about intentions, statistics, and all things the public or company needs to know.	1.3 Be honest and trustworthy.	We communicated every concern or question we had to our client who we worked with every week or our project advisor with whom we met biweekly.
Health, Safety, Well-Being	Practice all of the applicable safety procedures. Have the public's well-being at the forefront of every decision.	1.2 Avoid Harm.	Adhered to the electrical safety standards talked about at the beginning of this document.
Property Ownership	Only use technology you are permitted to use. Only give information out to people who are authorized to have it if permission is given by the owner of the information.	1.7 Honor Confidentiality. 2.8 Access computing and communication resources only when authorized or when compelled by the public good.	Our testing results, designs, plans, were never discussed with anybody outside of the group. All the software we needed was provided to us by ETG.
Sustainability	Think about how this decision will last in the long term, how long this technology will be relevant, and what	1.1 Contribute to society and to human-well-being, acknowledging that all people are	Made sure that our design was energy efficient and long lasting. Ensuring that the design is good to use for a

	long term impacts will be seen from the result of this decision.	stakeholders in computing.	while before new technology replaces it.
Social Responsibility	Think and act without discrimination, think about the target audience, users of the product and how it impacts them or what messages your project could send others.	1.4 Be fair and act not to discriminate.	We made our product more affordable even though the target audience would be people who have access to very expensive photoacoustic imaging systems.

Table 4 - Code of Ethics

One area our team performed well in is communication honesty. We all felt comfortable working together and working with our project contacts. When we had any concerns or anything that needed to be addressed, we did not hesitate to bring it to attention so that it could be worked on. Another way we demonstrated this is by asking many questions. We feel that we did an excellent job asking questions about technical information, changes in user needs, and what else we could be doing better to ensure the project moved along smoothly. These signify a strong performance in the communication honesty area because we were truthful and transparent with each other.

An area that our team could have performed better in was time management. We didn't show enough urgency, especially in the first semester. This left us in a time crunch towards the end of the project. It is never good to be in a huge rush because when you are in a rush you can miss details or not have time to make final changes that can improve the final product. For example, we wanted to have our final board be red because it looks nicer and more polished than a green board which is usually for prototypes and revision boards. But the red boards take longer to fabricate, and we didn't have enough time to wait for that at the end of the project.

7.2 Four Principles

	Beneficence	Nonmalificence	Respect for Autonomy	Justice
Medical Industry	Increasing accuracy of instruments can help detect diseases/conditions for patients.	Increased accuracy reduces the chances for false positives or negatives that can cause harm to the patient's recovery.	Improved image quality increases the amount that can be learned from the system.	Reducing the cost of the amplifier reduces the cost of the system, waterfalling to a reduced bill that can be more affordable for all patients.
Global, Cultural, and Social	Increase Duringd	Ensuring the amplifier	Intuitive silkscreen	Affordability and accessibility for

	accuracy can help with rapid detection of disease where it's not readily available.	doesn't harm individuals by emitting EMI that could disrupt other medical devices.	labeling and component placement to allow for users to see how it works.	all markets and communities.
Environmental	Long-lasting design reduces transport and material usage impacts of replacements.	Tried to minimize energy loss by designing a power supply specific to this circuit's needs.	Labeled switch on the board allows for power to be easily turned off to save power when not actively being used.	Doesn't have a significant impact on a specific region or area.
Economic	Made a cheaper alternative than is on the market right now.	Made sure the amplifier is long-lasting and doesn't have any parts that waste money.	Ensuring the users know how it works, why it works, and what repair or replacement might cost.	Made our product affordable for everybody who needs it to be able to use.

Table 5 – Broader-Context Principle

One broader-context principal pair that is important to our project is the beneficence in the medical industry. Generating a product that can improve the accuracy of the existing technology can help increase the speed of detection for diseases and conditions. Increased accuracy can also reduce the number of false positives and negatives which will greatly improve the usefulness of the technology and patient satisfaction.

The most important principle in our project was the cost and durability of the final product. Decreasing the cost means cost savings for the client and helps to continue the client's research so that it may be used in the future outside of the laboratory. Increasing durability and the lifespan of the project limits the user from having to replace the product which would cost money and time and leave a dead period where they cannot use the PAT device.

One broader context principal pair that is lacking in our project would probably be respect for autonomy in the economic space. This is mostly because we think it is hard to communicate with users of technology about this small piece inside of a bigger system. Non-experts in the field, which might be the company's CFO or someone who approves of buying this system will have no idea our design is even inside the larger PAT setup. To help with this we made the system extremely easy to use, with there only being one thing the user needs to change to setup the system besides plugging the cables into the SMA connectors: The power switch. We can also send information to potential customers/users and inform them. Resources, like this design document and the datasheet that we made for the product, would be able to help educate the users of the amplifier and how it fits into the overall system.

7.3 VIRTUES

Three virtues that were important to our team were honesty, commitment to quality, and commitment to the public good.

Honesty in terms of our project means each member being truthful and transparent about their thoughts on ideas and decisions. It also means being honest with us and what we are each capable of. We have done an excellent job communicating with each other and sharing opinions, concerns, and future plans while working on this project.

Commitment to quality means that we will not settle for anything less than the best that we can do in the time frame allotted to us in this class. We did our best to accomplish each group-assigned task as well as we can for the benefit of the group and for the users that need the project to be successful. Before testing, we made sure to test the connectivity of each component to the board and to their respective nets. This makes sure that the design is implemented correctly when assembling the boards and makes sure to maximize lifespan of the product. During testing, we made sure to run multiple trials of every test to ensure results do not vary. If the results varied every time the device was used, that would indicate bad design and would not be a good quality product.

Commitment to the public good entails making decisions while thinking of other's needs before ours. An example of this in our project is when we thought about designing a breaker circuit at the end of our amplifier to ensure that there's not too much power going back into the computer, which could potentially harm the user's equipment. At the end of the project, we realized that our design did not require that because the DC output voltage is at zero, but the thought was good.

Ryan: One virtue that I have demonstrated throughout our work is courage and work ethic. I was always enthusiastic about trying out new ideas that we have, or any work that we had to get done. I was always timely and got my parts done by the times that we agreed on. This is important to me because effort and willingness are important to get work done and are particularly essential in group projects, and I know what it's like to have group members who don't get their stuff done on time. One thing that I didn't demonstrate as much individually at the start of the project is patience. It can be very stressful with all the other schoolwork we all have and when I feel like we are behind where we want to be it is not easy to think calmly and clearly. This came into play at the end of the project when everyone on the team has a lot of work in other classes as well as this project. One way I showed improvement in this area is being flexible and understanding with when everyone could meet as the semester got busy before finals.

Ethan: One virtue that I have demonstrated through our works so far is honesty. This virtue is important to me because it can prevent miscommunication and prevent potential problems with the project from being hidden or minimized. I have demonstrated this virtue by representing our progress as accurately as possible, without trying to cover up for failures or trying to make our team look better. One virtue that I believe I have not demonstrated adequately is leadership. Leadership is important to me because it can help a team work together more effectively and reach their fullest potential. One thing I can do to demonstrate that virtue is to take responsibility for the work of the entire group as if it were my own, instead of focusing on my assigned portion of the project.

Yash: One virtue I have demonstrated throughout the project is perseverance. This virtue is important to me because it means that we must keep working towards meeting the client's demands and present the best amplifier we can. I have demonstrated this virtue by trying different capacitor and inductor values to determine which gets the best frequency response. One virtue I haven't shown and still need to explain is creativity. Creativity is essential because it helps me come up with ideas when the team is at a dead-end and can breathe new life into a project that seems impossible. One thing I can do to demonstrate this virtue is to study different aspects of other biasing circuits or amplifiers and apply them to this project.

Jonathan: One virtue that I have demonstrated in this project is open-mindedness. I have demonstrated this by being receptive to other group members' opinions and ideas. Different ideas helped us to find more and better ways to solve the design problems we faced. We were also able to find ways to explore the implementation of multiple ideas. This open-mindedness also fostered teamwork and improved the team dynamic. A virtue that I could have done better with is patience. When the end of the project came near, I could have been more patient with my other group members, who like me, had a lot of other projects to work on.

8. Conclusions

8.1. Summary of Progress

Our project goal was to develop a way to amplify the signal generated from a photoacoustic imaging system used for research here at Iowa State. This amplifier circuit needed to amplify a radio frequency or RF signal to generate higher-quality images, from which better conclusions can be drawn. Our design requirements included low noise, a gain greater than 30dB, 8 channels, 100kHz to 20MHz bandwidth, and a lower cost than the original system, while using the same family of amplifier components that have worked well for the client in the past. This project is intended to replace an old amplifier array with a new one that meets these requirements, which the last design did not.

8.2. Value Provided

This project is based on replacing an existing amplifier array with a new one that will be more cost effective, have a higher gain, and have lower noise. As an added benefit, the new design is also significantly smaller than the amplifier array it will be replacing.

In terms of cost effectiveness, the new design costs about $140 for an entire array, compared to the old design costing roughly the same amount per channel, which the array has 8 of. While the cost of the new design does not factor in the costs of the battery or the filament for the 3D printed housing, the old design also doesn’t include the cost of the power supply or housing, which is more expensive that the new design. This means a cost of roughly $1/8^{th}$ what it was previously. This cost does not factor in the cost of assembling the arrays, however, due to the limited number of arrays being necessary for the client’s needs, every necessary board could be assembled using a stencil and reflow oven in just a few hours.

The new amplifier array also has a slightly higher gain than the old, with a gain of about 32dB, compared to about 30dB with the old array. This gain can also be increased by cascading one amplifier into another and the board includes 2 partial channels that can be used to increase gain by a smaller amount than a full amplifier channel. This allows the user to determine the gain that is required for their application.

The old array had a major problem with its power distribution, as it used a switching regulator, which induced a relatively large amount of noise in the power plane. By using a battery or a benchtop power supply this issue should be avoided. The board is designed to work with 10V, however, the battery being used is 12V, which meant that a regulator was still necessary. In order to avoid noise the new design has a linear regulator, which doesn't add switching noise at the minor drawback of a little power efficiency.

The new design is also significantly smaller and lighter, with it being less than 8 inches long and under 3 inches wide, with a 3D printed housing, compared to the old array which was about 16 inches long and 4.5 inches wide, with its aluminum housing. The switch from aluminum to a 3D print does not affect the design's RF shielding, due to that being integrated with the board, and is expected to have minimal to no impact on the thermal dissipation of the amplifier array due to the low power usage.

8.3. Next Steps

While we have met the specifications given to us by our client, he may choose to improve the design further in the future. Our client has told us that he plans to add another stage to our working design to increase the gain even more, and tinker around with ways to increase the bandwidth as well. Adding an additional stage should be very easy, due to our inclusion of the two extra partial channels, which allow an extra stage on the amplifier to be tested before creating a new PCB. We believe that the cutoff frequency can be modified by changing the capacitor values of the system, something that can be tested and even implemented directly on our working board. There is also another senior design project one semester behind ours focused on the ADC of the system. Our design will help the to integrate all of the parts of the system together.

9. References

[1] Mini-Circuits, "Surface Mount Monolithic Amplifier," MAR-6SM+ datasheet.

[2] Mini-Circuits, "Surface Mount Monolithic Amplifier," MAR-3SM+ datasheet.

[3] IEEE Standards Association, "Standards," *IEEE Standards Association*, Available: https://standards.ieee.org/standard/ [accessed Dec. 7, 2024].

[4] Association for Computing Machinery, "ACM Code of Ethics and Professional Conduct," *Association for Computing Machinery*, Available: https://www.acm.org/code-of-ethics [accessed Dec. 7, 2024].

10. Appendices

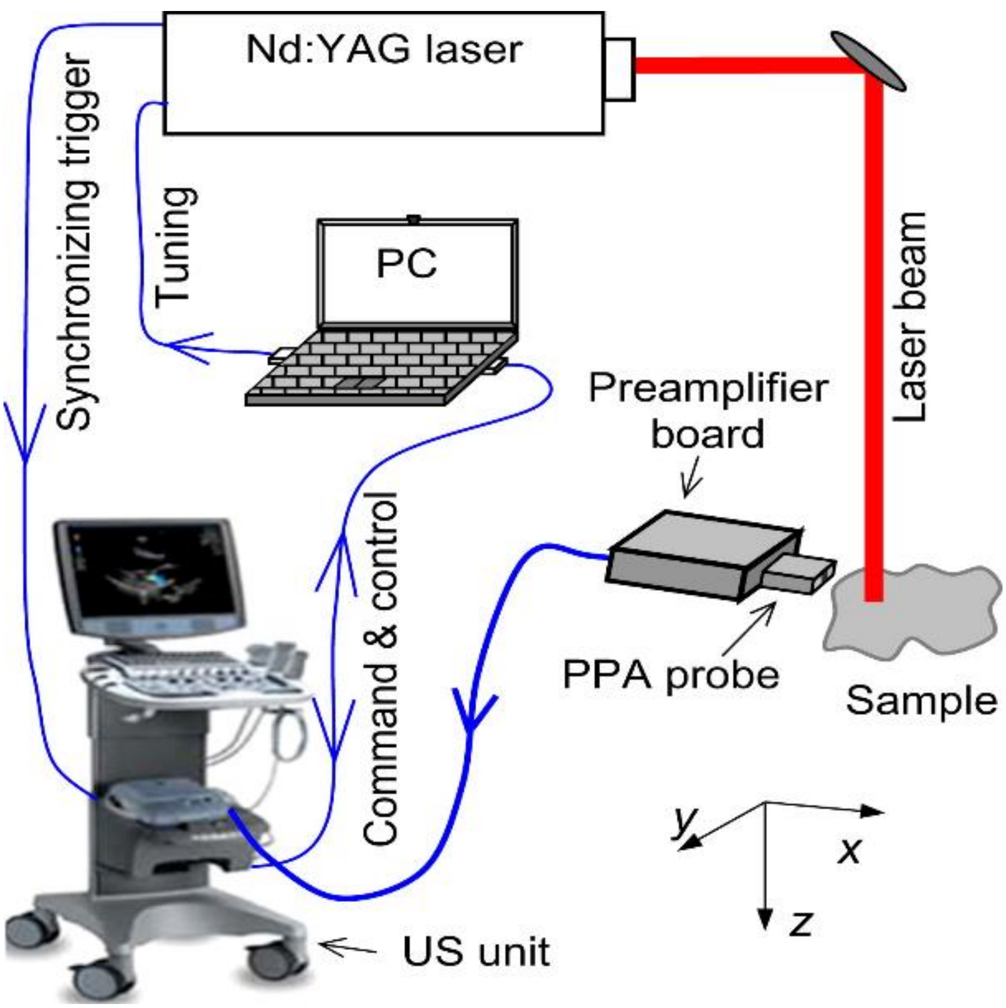
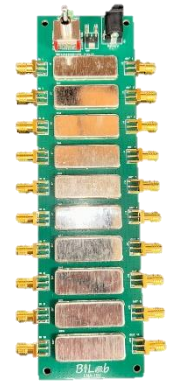


Figure 15 – The Amplifier's Place in the Completed System

Appendix 1 - Operation Manual

BILab LNA Datasheet



General Description

The BILab LNA 10V Amplifier is a low noise bandpass amplifier intended for use with a photoacoustic tomography machine. It offers 8 channels with a gain of 32.7dB as well as two channels with lower gain to be connected before (for channel 9) or after (for channel 10) the main channels to increase gain.

Channels 1-8

Parameter	Min.	Typ.	Max.	Units
Frequency Range	1.1		24.2	MHz
Gain		32.7		dB
Operating Current		51		mA
Operating Voltage		10	15*	VDC
Output Voltage Range	0		1.2	V_{PP}

Table 6 - Electrical Characteristics (Per Channel, Channels 1–8)

Channel 9

Parameter	Min.	Typ.	Max.	Units
Frequency Range	1.1		24.2	MHz
Gain		21.8		dB
Operating Current		16		mA
Operating Voltage		10	15*	VDC
Output Voltage Range	0			V_{PP}

Table 7 - Electrical Characteristics (Channel 9)

Channel 10

Parameter	Min.	Typ.	Max.	Units
Frequency Range	1.1		24.2	MHz
Gain		12.5		dB
Operating Current		35		mA
Operating Voltage		10	15*	VDC
Output Voltage Range	0		1.8	V_{PP}

Table 8 - Electrical Characteristics (Channel 10)

*For operation with 15 volts the biasing resistors must be swapped out according with the Mini-Circuits MAR-6SM+ and MAR-3SM+ datasheets.

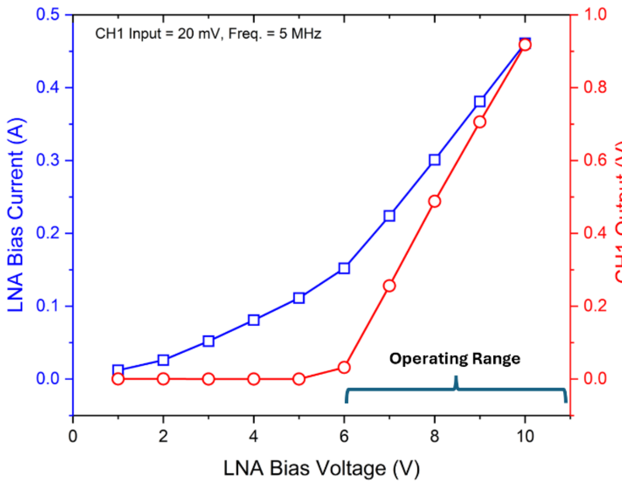


Figure 16 - Bias Voltage vs. Bias Current and Output Voltage

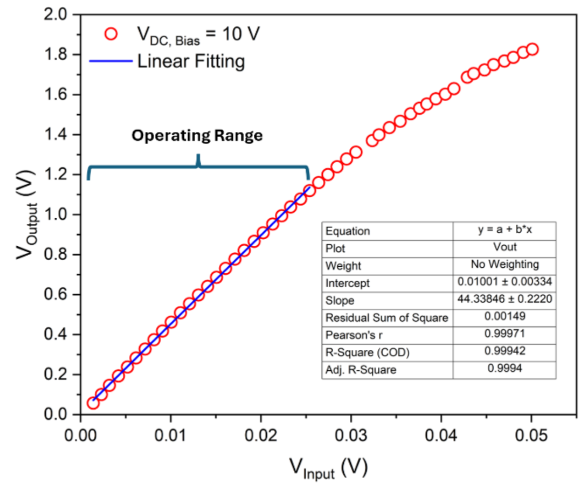


Figure 17 - Input Voltage vs. Output Voltage

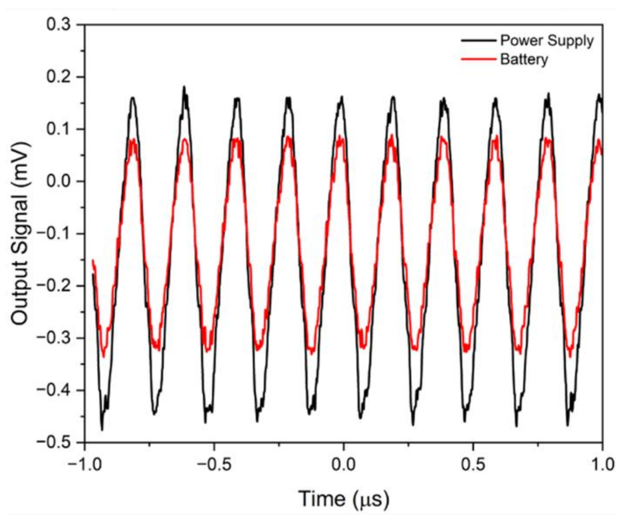


Figure 18 - Output Noise Benchtop Supply vs. Battery

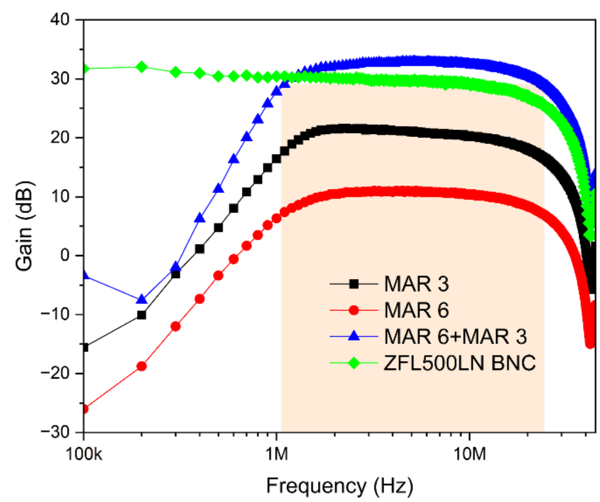


Figure 19 - Bandwidth and Gain

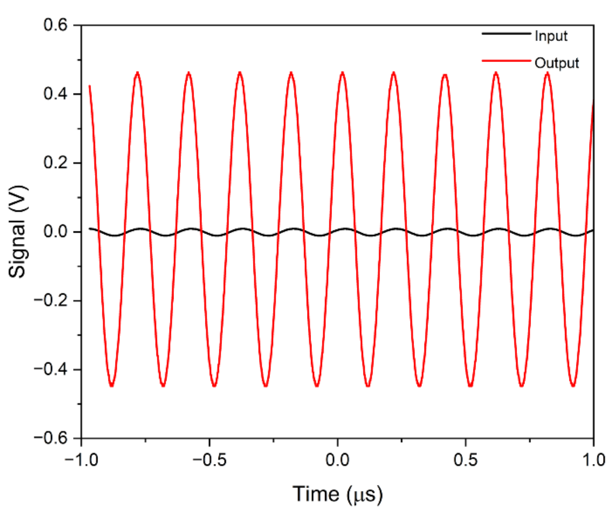


Figure 20 - Amplification of the Signal

Appendix 2 - ALTERNATIVE/INITIAL VERSION OF DESIGN

These graphs are from testing that we performed on the prototype board provided to us.

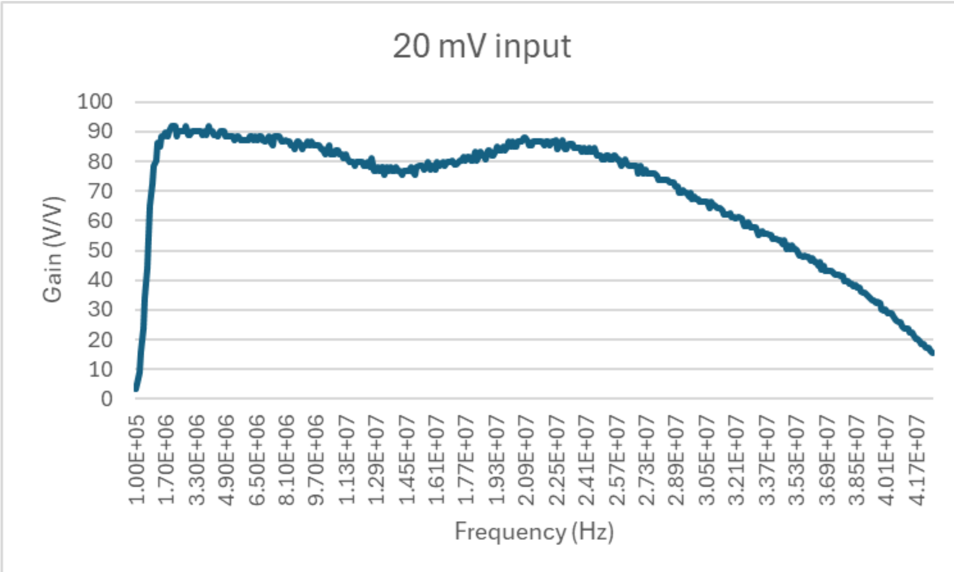


Figure 21 - Original Prototype AC Sweep

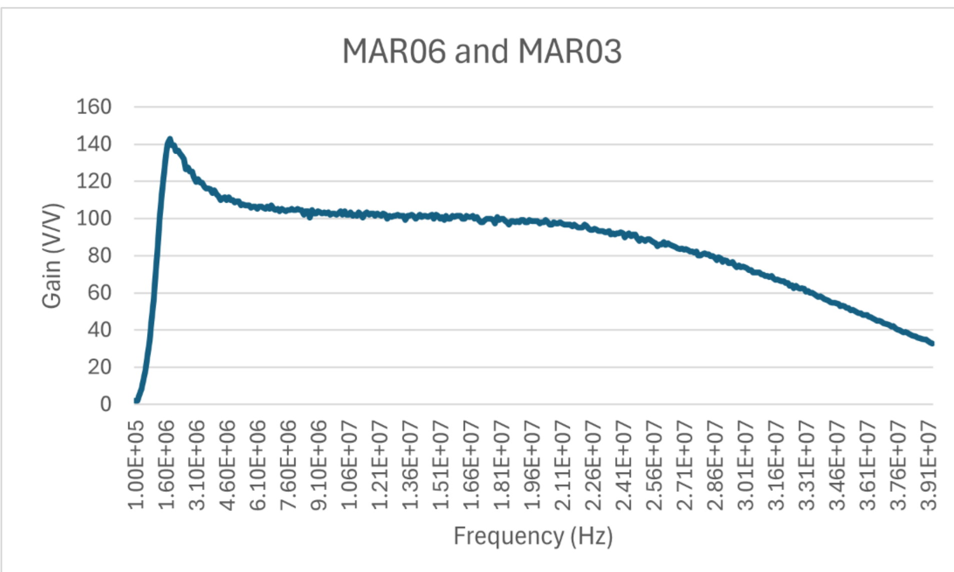


Figure 22 - Prototype Board with Different Stage 1 and Stage 2 Amplifiers

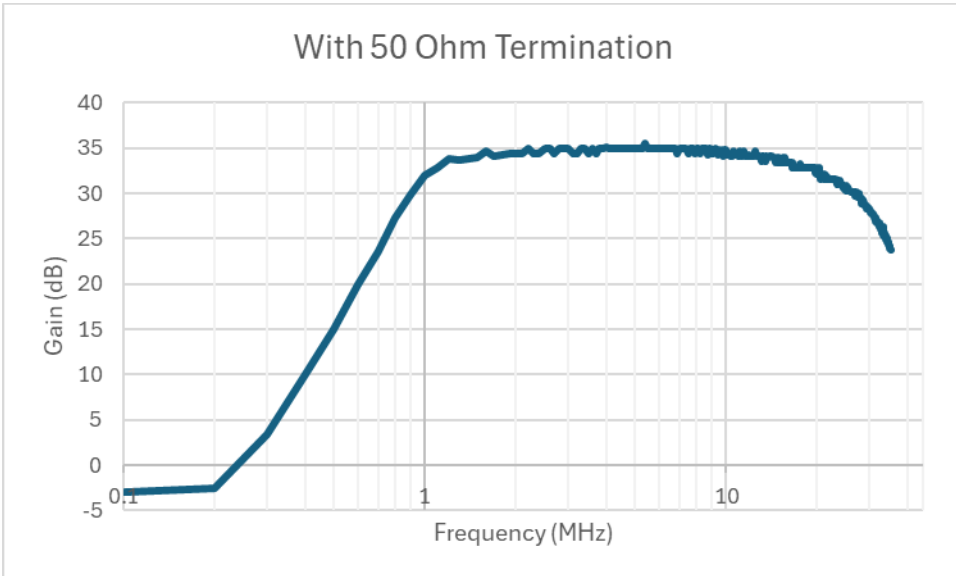
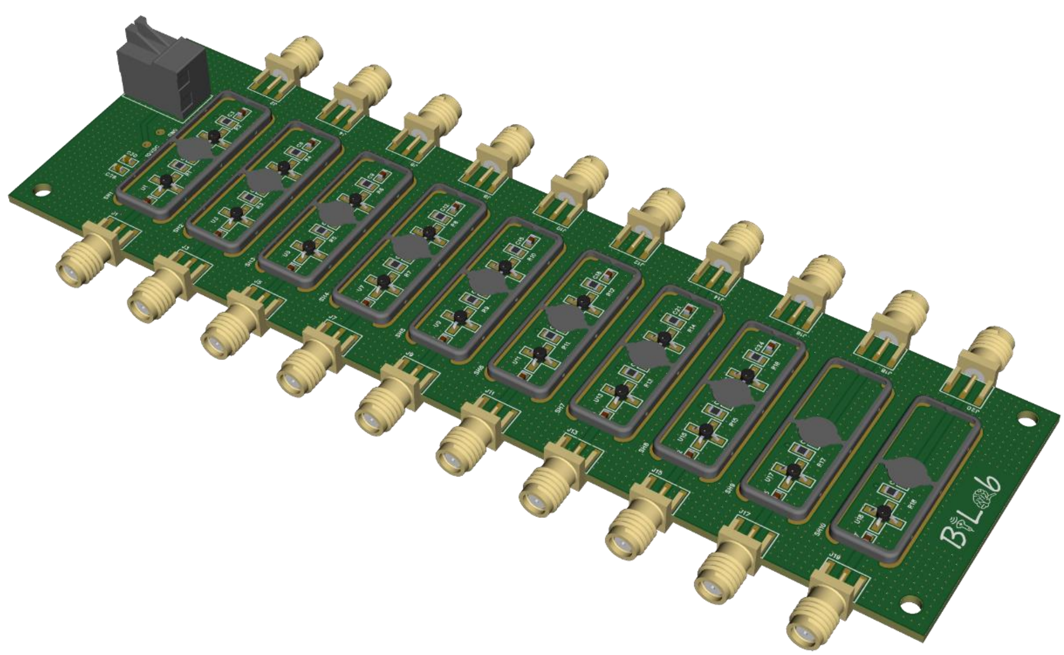


Figure 23 - Prototype Board with 50 Ohm Termination on Oscilloscope

The first board we designed can be seen below. This board is very similar to the final design but lacked the power distribution system of the final board and also had a few issues that were solved in the second version.



Appendix 3 - Other Considerations

The requirements for this design changed a lot over the course of the project. We were originally given one set of requirements, but as the project went on the client changed them. The most important changed constraint is that of the gain. The client originally wanted over 100V/V of gain, corresponding to 40dB, but later decided that a lower gain was acceptable. This was not due to us believing that the gain requirement was impossible, but rather based on the client wanting to focus on solving other problems first and then later increasing the gain if necessary.

The original design requirements for this project were:

Functional Requirements:

- Low noise: Less than 2 dB
- Low input impedance: About 50 Ohms
- Bandpass filtering: 10kHz-10MHz (Constraint)
- High Gain (~100 to ~10000 V/V) (Constraint)
- Output voltage must be less than 10 V
- Handling input voltages from 100 μV to 10 mV

Physical Requirements:

- Protection from ESD and EM interference
- Small size (< 5x5 cm each) (Constraint)
- Modularity - Usable with 8 or 16 amplifiers (Constraint)
- Thermal Dissipation
- Ability to mount on PAT machine

User Experience Requirements:

- Low maintenance
- Easy to set up
- Modularity ensures the ability to change components easily

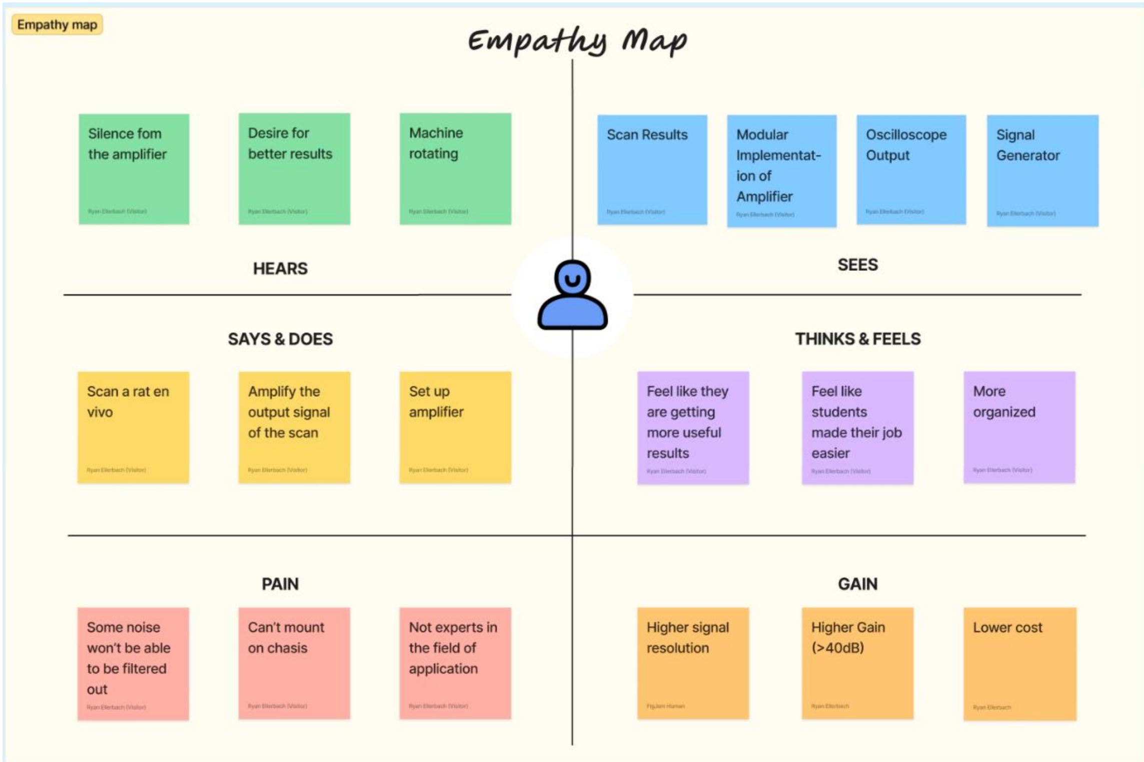


Figure 24 - Empathy Map

Appendix 4 - Team Contract

Team Members

Ethan Hulinsky

Jonathan Wetenkamp

Ryan Ellerbach

Yash Gaonkar

Required Skill Sets for Your Project

For this project, the team demonstrated several technical and soft skills. This included technical skills like Circuit Design and Analysis, Signal processing, and PCB design, as well as soft skills like critical thinking and team collaboration.

Circuit Design and Analysis: The team had to design and test amplifier circuits under a variety of stimuli.

Simulation Tool Proficiency: Our team used the software NI-Multisim to simulate different testing parameters.

Lab Equipment Proficiency: The team had to use lab software tools like LabVIEW to see the frequency response of the circuit. The team had to use Oscilloscopes, multimeters, signal generators, and other lab equipment to run different tests on the prototype.

Power Electronics: The team had to know the basics of power electronics to design the battery-operated power supply of the circuit.

PCB design: We had to know about PCB design to understand how the prototype board worked, how to design the test board, and design a final board.

Soldering: The prototype board had to be modified in testing and the team also had to assemble the test board by hand and use a solder mask and reflow oven to assemble the final boards.

Critical Thinking: The team had to use critical thinking on several occasions to analyze different design Trade-Offs.

Problem Solving: The team used problem-solving to solve a variety of issues, including clipping, noise, unexpected values for gain, and more.

Adaptability: The team had to adapt to the different requirements or feedback from the client and the advisor, as well as to issues that came up. An example of this is that the client preferred the use of a specific amplifier on the board, one that the team could not simulate as well as desired due to being unable to acquire the spice simulation file for the board.

Documentation: The team had to document all the weekly progress reports as well as the design docs and notes from the advisor meetings

Skill Sets covered by the Team

Yash: Circuit Analysis, Lab Equipment, Power Electronics, Documentation, Problem Solving, Adaptability, Critical Thinking

Ryan: Circuit Analysis, Lab Equipment, Power Electronics, Documentation, Problem Solving, Adaptability, Critical Thinking, PCB design, Simulation Tool Proficiency

Ethan: Circuit Analysis, Lab Equipment, Power Electronics, Documentation, Problem Solving, Adaptability, Critical Thinking, PCB design, Simulation Tool Proficiency

Jonathan: Circuit Analysis, Lab Equipment, Power Electronics, Documentation, Problem Solving, Adaptability, Critical Thinking, PCB design, Simulation Tool Proficiency

Project Management Style Adopted by the team

We had a waterfall and agile project management mix for the Project Management style. Typically, the waterfall is a style of project management where the team sets certain deadlines, which normally don't change. Due to the nature of PCB testing and design, we were not always able to expect issues that would arise and the deadlines we were able to set focused on the big picture things, similar to an agile project management style. However, the team wasn't able to simply stick to the agile style, as many of the tasks required for the project depended on the tasks before them being completed. This meant that while the team knew the next step and the end goal, there wasn't always a simple answer to get from one to the other and there was rarely another task that could be worked on in tandem with the primary task. This sometimes led to delays and also led to a time crunch at the end of the project.

Initial Project Management Roles

Yash: Team Organization

Ryan: Client Interaction, Testing

Ethan: Part Orders, Assembly

Jonathan: Testing, Design

Team Contract

Team Procedures

1. Day, time, and location (face-to-face or virtual) for regular team meetings:

12:00 on Mondays, in person in the TLA in Coover.

2. Preferred method of communication updates, reminders, issues, and scheduling (e.g., e-mail, phone, app, face-to-face):

Text messages in the group chat, as well as face to face updates.

3. Decision-making policy (e.g., consensus, majority vote):

The majority voted to decide when the group doesn't completely agree.

4. Procedures for record keeping (i.e., who will keep meeting minutes, how will minutes be shared/archived):

Yash will keep records and will share a google doc.

Participation Expectations

1. Expected individual attendance, punctuality, and participation at all team meetings:

All team members are expected to attend all meetings and arrive within 5 minutes of the agreed upon start time. If a team member can't make a meeting notice of absence is expected an hour ahead of time. If a team member will be later than 5 minutes late, it is expected that they notify the group as soon as possible.

2. Expected level of responsibility for fulfilling team assignments, timelines, and deadlines:

All team members are expected to complete individual assignments and participate in completing group assignments in pace with the agreed upon timeline.

3. Expected level of communication with other team members:

Team members are expected to communicate any issues they have so that the group does not fall behind as well as reply in a timely manner.

4. Expected level of commitment to team decisions and tasks:

Each team member is expected to be present and prepared to help with all team decisions and tasks.

Leadership

1. Leadership roles for each team member (e.g., team organization, client interaction, individual component design, testing, etc.):

Yash: Team Organization

Ryan: Client Interaction

Ethan: Individual Component Design

Jonathan: Testing

2. Strategies for supporting and guiding the work of all team members:

Team members are expected to create an open and engaging environment where the group will help any team member who needs it. To facilitate this, team members are encouraged to reach out for help if they know they will need it.

3. Strategies for recognizing the contributions of all team members:

Team members will be congratulated for all work that is done.

Collaboration and Inclusion

1. Describe the skills, expertise, and unique perspectives each team member brings to the team.

Yash has expertise and interest in VLSI, which can help with the modularity constraint on the project. Ryan, Jonathan, and Ethan all have experience in PCB design which is a lot of what this project will entail. We all have taken different classes and many have different sequences which will give us a variety of perspectives and expertise.

2. Strategies for encouraging and supporting contributions and ideas from all team members:

All team members are expected to contribute as much as possible as well as encourage others to contribute whenever they can.

3. Procedures for identifying and resolving collaboration or inclusion issues (e.g., how will a team member inform the team that the team environment is obstructing their opportunity or ability to contribute?)

Team members should bring up any issues they have as soon as possible and the group will discuss solutions. Teammates are also encouraged to identify any other issues with another member they see so that the group is aware. The group is then expected to meet and discuss what they believe the best solution will be.

Goal-Setting, Planning, and Execution

1. Team goals for this semester:

Learn useful skills from the project and complete as much of the project as possible. Another goal is to take pride in our work and at the end of the year have a project that the team is proud of.

2. Strategies for planning and assigning individual and team work:

Break down our next task into individual steps and then categorize based off of time/difficulty and then distribute to those best suited for each task.

3. Strategies for keeping on task:

Keeping weekly meetings brief and to the point to give time for us to finish our other work outside of the time spent for this project.

Consequences for Not Adhering to Team Contract

1. How will you handle infractions of any of the obligations of this team contract? What will your team do if the infractions continue?

First major infraction: Brought up and discussed at team meeting

Repeated minor infractions: Discussed at weekly team meeting

Repeated major infractions: Discussed with team member first, then brought to the advisor and professors teaching the class

****

a) *I participated in formulating the standards, roles, and procedures as stated in this contract.*

b) *I understand that I am obligated to abide by these terms and conditions.*

c) *I understand that if I do not abide by these terms and conditions, I will suffer the*

consequences as stated in this contract.

1) ________Ryan Ellerbach______________________________ DATE ______9/17/24__

2) ________Jonathan Wetenkamp__________________________ DATE ______9/17/24_____

3) ______ Yash Gaonkar________________________________ DATE ______9/17/24______

4) ______ Ethan Hulinksy _____________________________ DATE ______9/17/24______