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Guitar Headphone Amplifier

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1 Abbreviations and Acronyms

- **GHA** – Guitar Headphone Amplifier
- **PCB** – Printed Circuit Board
- **DC** – Direct Current
- **CAD** – Computer-Aided Design
- **DPDT** – Double Pole-Double Throw
- **SPDT** – Single Pole-Double Throw
- **THD** - Total Harmonic Distortion
- **EMI** - Electromagnetic Interference

Abstract

This report details the development and implementation of a Guitar Headphone Amplifier, a specialized audio device engineered to provide musicians with high-quality personal monitoring capabilities. The amplifier features a dual-power system, accommodating both battery operation and external DC power supply, ensuring versatility across different usage scenarios. The design incorporates two distinct variable gain settings to accommodate various playing styles and output requirements. Although the primary design specifications focus on a battery-operated amplifier with 2 fixed gain settings, an additional features has been integrated to allow operation with an external DC adapter and small speaker driving capability. The design process involved comprehensive validation through Cadence PSpice simulations, with the physical implementation utilizing Altium for PCB layout and SolidWorks for enclosure design.

Contents

2 Introduction and Functionality

2.1 Overview

The Guitar Headphone Amplifier (GHA) is a versatile audio processing device designed specifically for guitarists who need high-quality personal monitoring. It converts guitar signals into amplified mono output, enabling private practice sessions through headphones in any environment without compromising sound quality. Through careful circuit design, the amplifier maintains signal integrity with minimal distortion, delivering clear and accurate guitar tones.
Featuring dual power options, the device can operate on either two 9V batteries or a 12V DC power supply, offering flexibility for both mobile and stationary use. While primarily designed for headphone monitoring, the amplifier delivers up to 10W of power output, making it capable of driving small speakers for practice and monitoring applications. This combination of portability, power options, and output flexibility makes it an ideal solution for practice sessions, recording scenarios, and intimate performance settings.

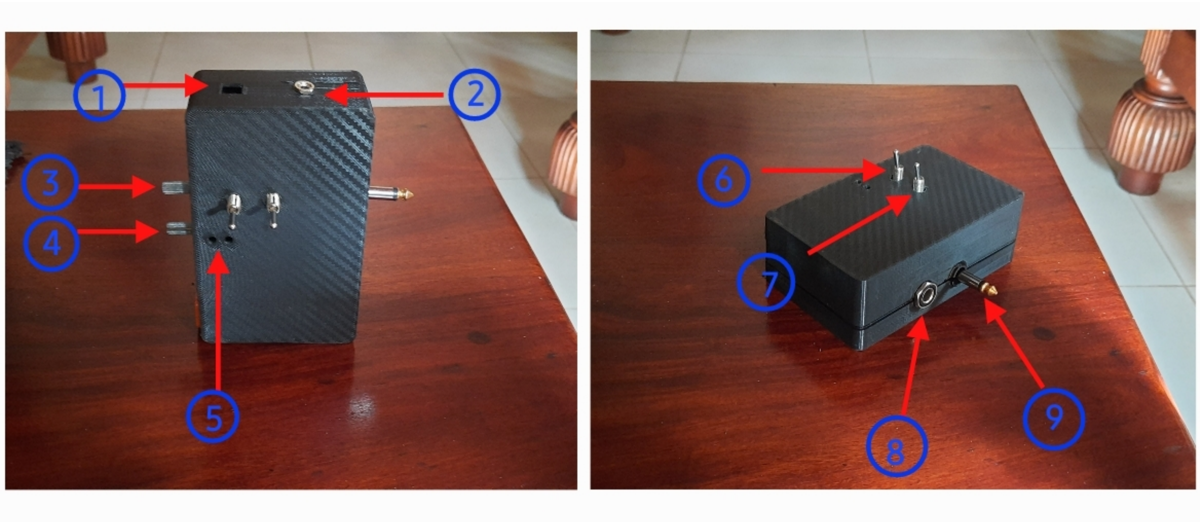


Figure 1: End Product View

1. 12V DC input barrel jack
2. 1/8" mono audio output socket
3. Gain adjuster in headphone mode
4. Level 2 gain adjuster in speaker mode
5. Power mode LED indicators
6. Power mode selector toggle switch
7. Amplifier mode selector toggle switch
8. 1/4" mono audio input socket
9. 1/4" mono audio input jack

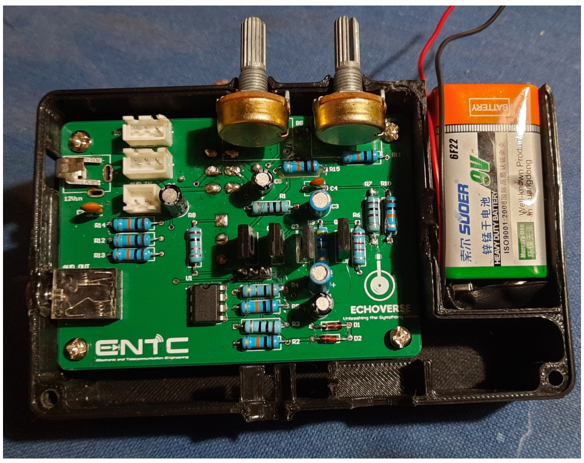


Figure 2: Internal view with bare PCB

2.2 Audio input & output

The GHA features dual input options through a 1/4" (6.35mm) mono audio socket and jack, which are internally connected. Both input terminals are strategically positioned on the same side of the enclosure to prevent simultaneous connection of two input devices, eliminating potential signal interference.
For output, the circuit utilizes a 1/8" (3.5mm) stereo audio socket configured in mono mode through internal short-circuiting of its channels.

2.3 Power modes

The GHA consists of 2 power modes. Device can be powered by two 9V batteries or 12V external DC power supply. Switching between them and turning off the device can be done by the power mode selector DPDT (On-Off-On) toggle switch ; presented by 6 in figure 2.
In the battery mode, the negative and positive voltage is supplied by negative and positive terminal of 2 different batteries, while keeping one of opposite polarity terminals from each battery common.
In the 12V external supply mode, power to the circuit is terminated via 12V DC barrel jack and a separated inverting buck-boost converter circuit will be employed to get the negative polarity supply required for the op-amps and the class AB amplifier. A separate inverting circuit will be connected to the circuit to the connector designated as "INVTR" in the PCB.

2.4 Amplifier modes

The GHA features two distinct amplification modes: headphone and speaker, selectable via an SPDT (Single Pole Double Throw) On-On toggle switch. Each mode implements different gain structures optimized for its intended output device.

Headphone Mode: The signal path consists of two stages: a fixed-gain buffer followed by a variable-gain amplifier. The buffer stage maintains a constant gain of 2x:

$$A_b = 1 + \frac{R8}{R4} = 1 + \frac{1k\Omega}{1k\Omega} = 2$$

The second stage employs a non-inverting amplifier configuration with a 10kΩ potentiometer, providing variable gain from 1x to 11x:

$$A_a = 1 + \frac{AMPG}{R10} \qquad \therefore A_{aMin} = 1 + 0 = 1 \quad , \quad A_{aMax} = 1 + \frac{10k\Omega}{1k\Omega} = 11$$

The cascaded stages result in an overall voltage gain range:

$$A = A_b A_a$$

$$\therefore A_{min} = 2 * 1 = 2 \qquad A_{max} = 2 * 11 = 22$$

Laboratory testing confirms that the Class AB output stage successfully drives 8Ω headphones rated at 1W across the entire gain range.

Speaker Mode: In this configuration, the buffer stage acts as a pre-amplifier with variable gain from 1x to 11x:

$$A_b = 1 + \frac{BG}{R4} \quad \therefore A_{bMin} = 1 + 0 = 1 \quad A_{bMax} = 1 + \frac{10k\Omega}{1k\Omega} = 11$$

The second stage maintains its previous configuration. This results in an expanded overall voltage gain range:

$$\therefore A_{min} = 1 * 1 = 1 \qquad A_{max} = 11 * 11 = 121$$

Note: All gain values refer to voltage gains, where A_b, A_a, and A represent buffer gain, non-inverting amplifier gain, and overall gain respectively. Component designations correspond to the final circuit implementation shown in figure 12

The implementation of distinct gain modes serves as a critical safety feature in the GHA design. The headphone mode deliberately limits the maximum voltage gain to 22x, protecting sensitive headphone drivers from potential damage that could occur at higher voltages. In contrast, the speaker mode allows for substantially higher voltage gains up to 121x, necessary for driving speakers effectively. This dual-mode approach ensures optimal and safe operation regardless of the output device connected.

3 System Architecture

3.1 Block Diagram

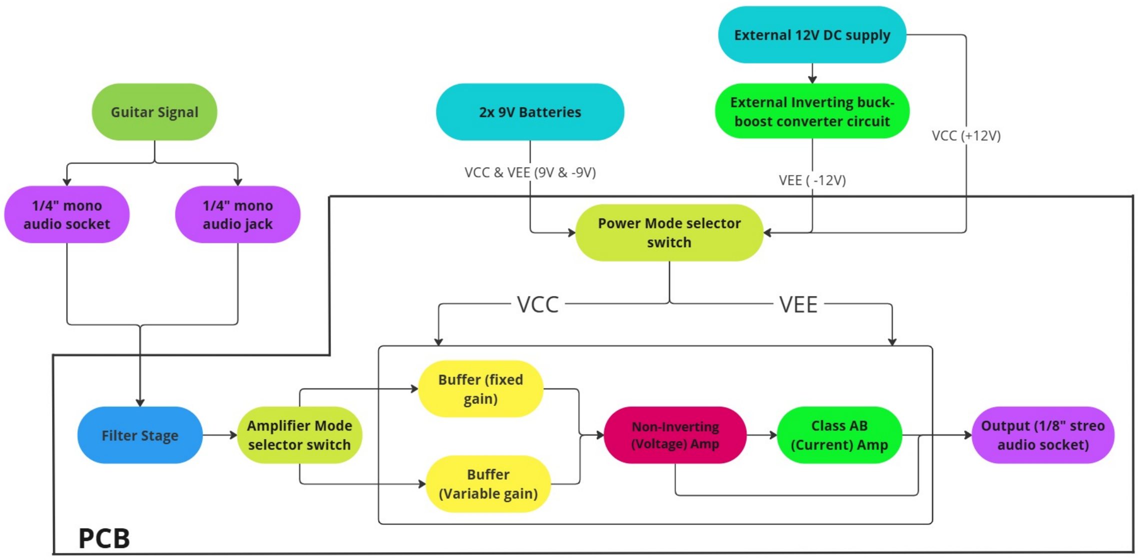


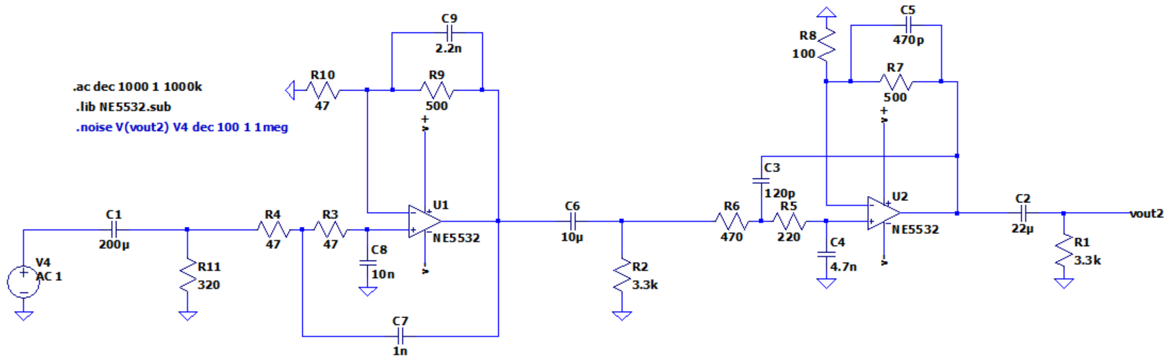
Figure 3: System block diagram

4 Design Stages

The design process for this guitar headphone amplifier underwent several stages before reaching the final implementation. Our objective was not only to meet the baseline requirements but also to exceed them by designing an amplifier capable of driving a small speaker, requiring sufficient power output and audio quality.

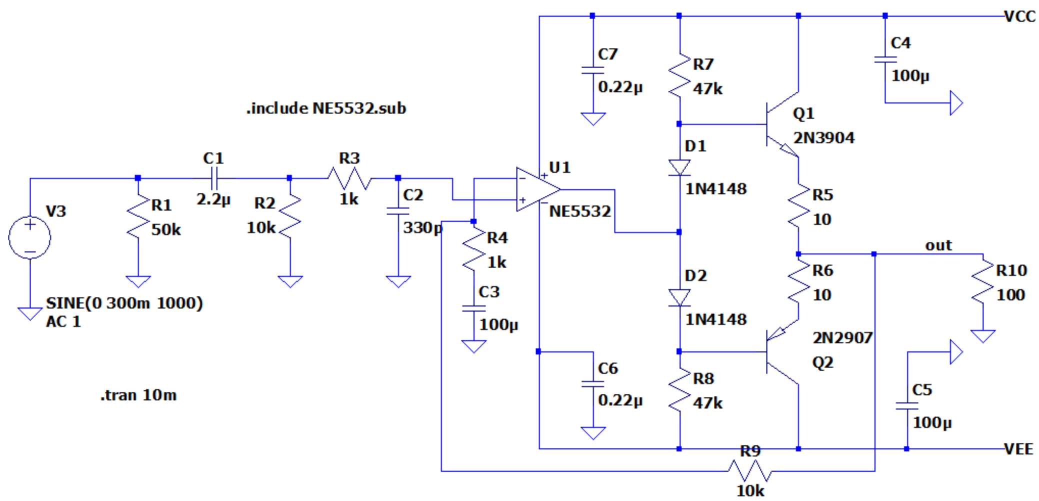
Using Two Op-Amps

The initial design utilized two NE5532 operational amplifiers configured to deliver adequate amplification for headphone use. However, during testing, it was observed that while the output was sufficient for headphones, it lacked the power required to drive a small speaker effectively. This limitation prompted the need for further design enhancements.



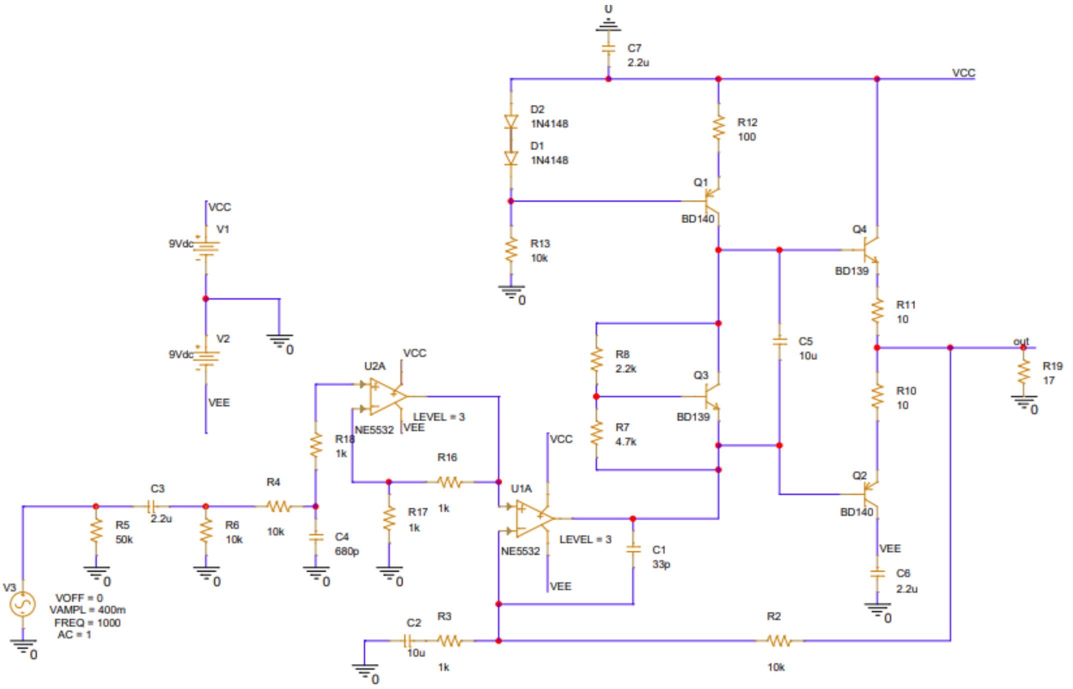
Class AB Audio Driver with NE5532

In the second stage, the design was upgraded to include a single NE5532 op-amp coupled with a class AB amplifier. The class AB configuration provided improved efficiency and higher output power compared to the initial design. This setup significantly enhanced the ability to drive a small speaker, but testing revealed noticeable crossover distortion at lower volumes, which affected audio quality. Addressing this issue led to the third design stage.



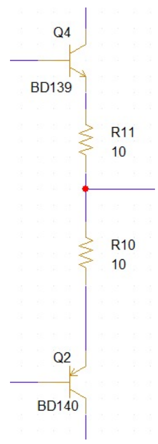
Final Stage

The final stage involved the implementation of a two-stage class AB amplifier. This configuration aimed to eliminate crossover distortion and further improve audio quality and power output.

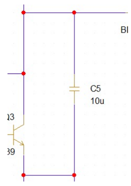


4.1 Key-points in the schematic

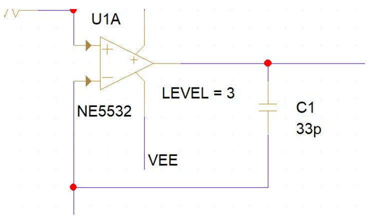
We used the push-pull output stage because it provides high efficiency, good power handling, and low distortion. It operates using two transistors, one for the positive half cycle (push) and the other for the negative half cycle (pull). This reduces power loss and ensures a balanced output, which is ideal for driving low impedance loads. The symmetrical design minimizes distortion, making it suitable for our requirments.



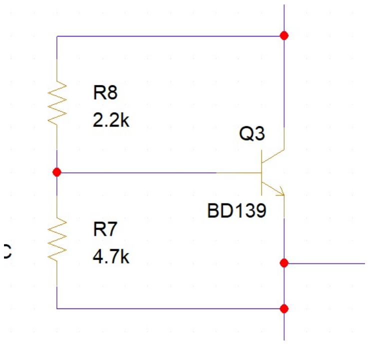
Purpose of this **C5** capacitor is to make sure the same ac signal is seen by both transistors at the output stage despite the effect of dc levels.

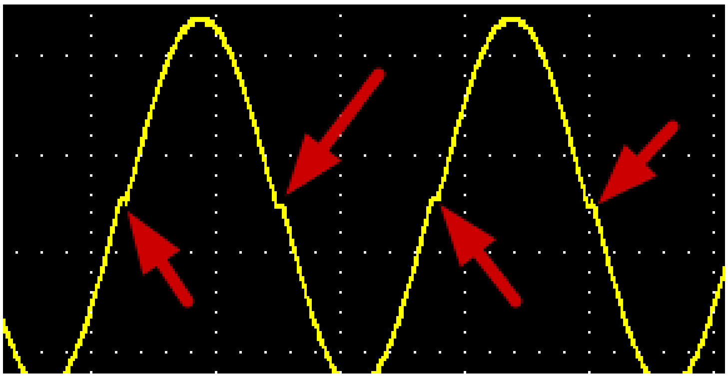


We have added this extra capacitor **C1** to stabilize the Op-Amp after referring to this article [9]. At low gains a significant effect of this capacitor cannot be seen but at high gains it can help the Op-Amp to be stable.



Crossover distortion is caused by switching between devices driving a load. It is very common in Class B, AB amplifiers.There are many solutions for this effect as using resistor/diode to bias the transistor. But we have added another transistor for biasing purpose and gaining more power.





5 Component Selection

5.1 Operational Amplifier

Selected Component: **NE5532**

Selecting the op-amp was challenging due to various factors such as noise, bandwidth, slew rate, and availability in the local market. A comparison of suitable op-amps is shown in Table 1.

Parameter	**NE5532[3]**	**LM4562[2]**	**TL072[4]**	**OPA797[1]**
Noise Voltage (nV/$\sqrt{\text{Hz}}$)	5	2.7	18	2.5
Slew Rate (V/μs)	9	20	13	20
GBP (MHz)	10	55	3	110
CMRR (dB)	100	120	80	130
THD (%)	0.002	0.00003	0.003	0.0001
Input Bias Current (nA)	200	10	65	0.2
Output Drive Capability (mA)	38	26	10	10
PSRR (dB)	100	120	80	120
Price (Rs)	50	150	60	1200
Availability	Yes	Rare	Yes	No

Table 1: Comparison of NE5532, LM4562, TL072, and OPA797 for Audio Amplifier Applications.

Considering the availability of this Op-Amps we can see the best choice is LM4562 but it is rare to find. So we had to choose between NE5532 and TL072. When Comparing them NE5532 has advantages in Noise performance, THD, Output Drive Capability and CMRR. There are other factors as well but here those are the most important. So our final choice was NE5532

5.2 Transistors

Selected Components - **BD140 and BD139 Complementary Pair**

We had to select a suitable transistor for our project as we were going beyond the requirements of the project, and the transistors must be a complementary pair, as we used a class AB (push-pull) amplifier.

Parameter	**BD139 (NPN)[5]**	**BD140 (PNP)[6]**	**TIP41 (NPN)[7]**	**TIP42 (PNP)[8]**
Type	NPN	PNP	NPN	PNP
Voltage Rating	80V	80V	40V, 60V, 100V	40V, 60V, 100V
Collector Current	1.5A	1.5A	6A	6A
Power Dissipation	12.5W	12.5W	65W	65W
Gain	25-250	25-250	15-75	15-75
Transition Frequency	190 MHz	190 MHz	3 MHz	3 MHz
Thermal Resistance	10	10	2	2
Package	TO-126	TO-126	TO-220	TO-220

Table 2: Comparison of BD139/BD140 and TIP41/TIP42 Transistors.

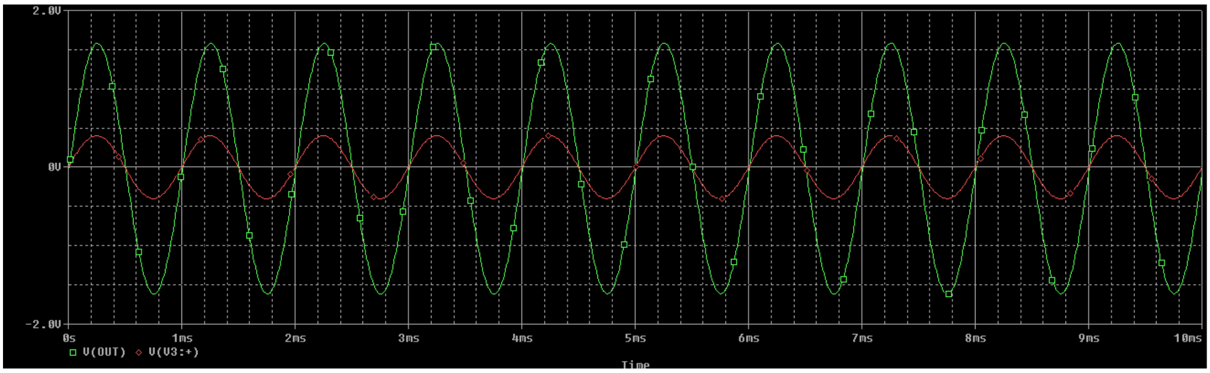
When it comes to transistor these BD139-BD140 and the TIP41-TIP42 are the common complementary pair available in the market. But this TIPxx is power transistors that can go up to 65W power. But at this moment we dont need that much of power rating. So we had to go with BD139/140. Most importantly the $\beta(\mathrm{h_{FE}})$ can be vary even if it is a complementary pair.

6 Software Simulation and Hardware Testing

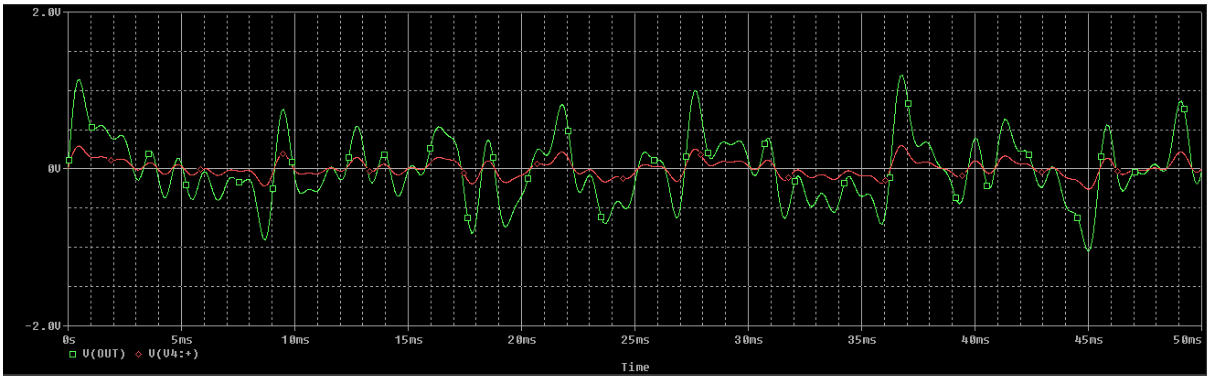
6.1 Software Simulation

6.1.1 Transient Analysis

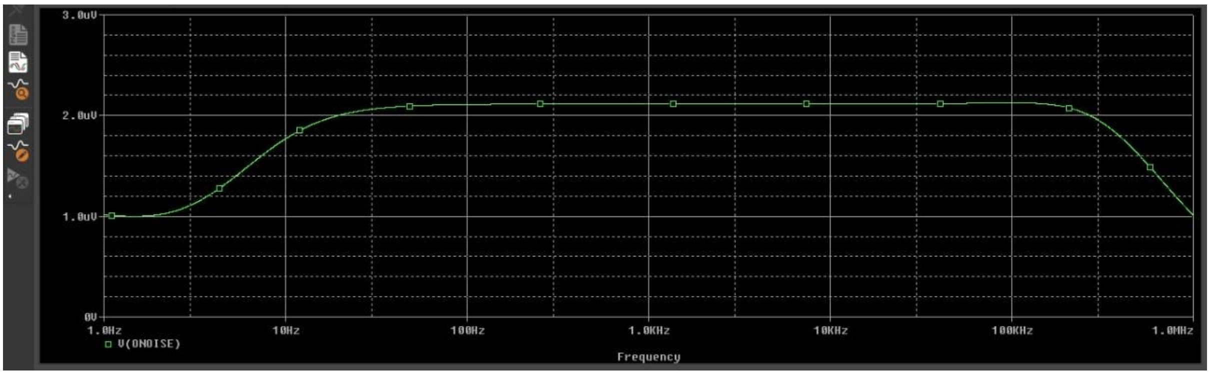
1. Transient Analysis Done with 400mV p-p Sinusoid Signal



2. Transient Analysis with Artificially Generated PWL signal with 0-4 kHz 0-500 mV signal.



6.1.2 Noise Analysis



6.1.3 Total Harmonic Distortion

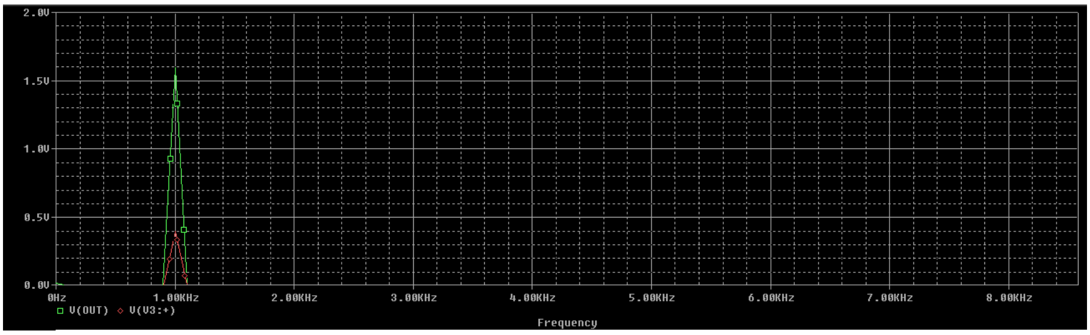


Figure 4: For a pure sine wave

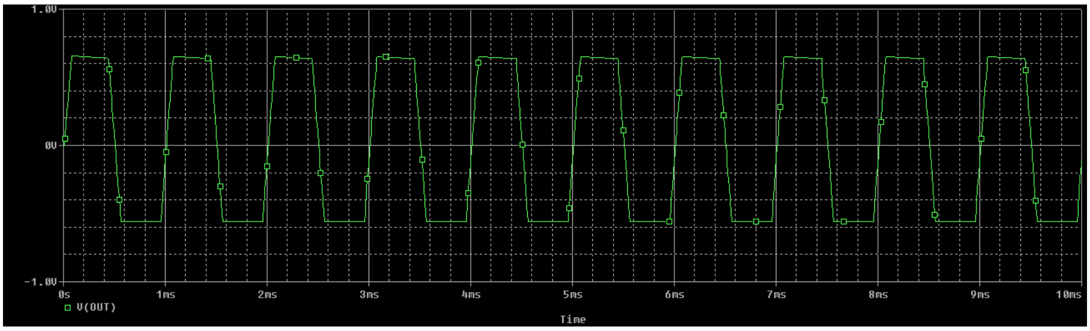


Figure 5: Distorted Wave as Driving a Low Z Load

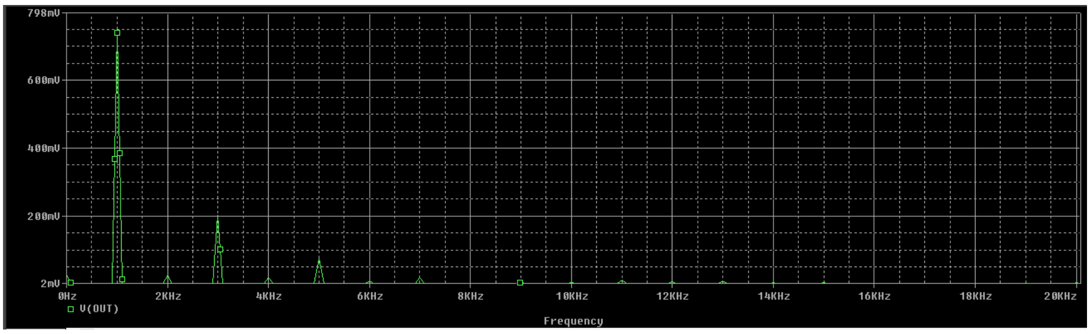


Figure 6: THD for saturated wave

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.0000E+03	1.5970E+00	1.0000E+00	-2.4315E+00	0.0000E+00
2	2.0000E+03	8.7319E-05	5.4676E-05	-3.5475E+01	-3.0612E+01
3	3.0000E+03	6.5340E-04	4.0914E-04	-9.8806E+01	-9.1511E+01
4	4.0000E+03	9.2356E-05	5.7831E-05	-1.2785E+02	-1.1812E+02
5	5.0000E+03	6.1630E-04	3.8591E-04	-1.0610E+02	-9.3943E+01
6	6.0000E+03	9.9242E-05	6.2142E-05	-1.4050E+02	-1.2591E+02
7	7.0000E+03	5.8033E-04	3.6338E-04	-1.1177E+02	-9.4752E+01
8	8.0000E+03	1.0315E-04	6.4591E-05	-1.4940E+02	-1.2995E+02
9	9.0000E+03	5.5870E-04	3.4984E-04	-1.1766E+02	-9.5780E+01
10	1.0000E+04	1.1177E-04	6.9986E-05	-1.5739E+02	-1.3307E+02
11	1.1000E+04	5.3765E-04	3.3666E-04	-1.2321E+02	-9.6463E+01
12	1.2000E+04	1.1740E-04	7.3514E-05	-1.6361E+02	-1.3443E+02
13	1.3000E+04	5.2054E-04	3.2595E-04	-1.2882E+02	-9.7212E+01
14	1.4000E+04	1.2424E-04	7.7796E-05	-1.7221E+02	-1.3817E+02
15	1.5000E+04	5.0457E-04	3.1595E-04	-1.3477E+02	-9.8298E+01

TOTAL HARMONIC DISTORTION = 9.5963E-02 PERCENT

HARMONIC NO	FREQUENCY (HZ)	FOURIER COMPONENT	NORMALIZED COMPONENT	PHASE (DEG)	NORMALIZED PHASE (DEG)
1	1.0000E+03	7.4682E-01	1.0000E+00	-3.3869E+00	0.0000E+00
2	2.0000E+03	2.6375E-02	3.5317E-02	-9.1633E+01	-8.4859E+01
3	3.0000E+03	2.0252E-01	2.7117E-01	-1.0968E+01	-8.0725E-01
4	4.0000E+03	1.8847E-02	2.5237E-02	-1.0322E+02	-8.9668E+01
5	5.0000E+03	7.5306E-02	1.0084E-01	-1.8256E+01	-1.3216E+00
6	6.0000E+03	9.0460E-03	1.2113E-02	-1.1393E+02	-9.3609E+01
7	7.0000E+03	1.8722E-02	2.5068E-02	-2.4762E+01	-1.0540E+00
8	8.0000E+03	5.0600E-04	6.7754E-04	1.6275E+02	1.8985E+02
9	9.0000E+03	6.2587E-03	8.3804E-03	1.4378E+02	1.7426E+02
10	1.0000E+04	5.5137E-03	7.3828E-03	5.7193E+01	9.1062E+01
11	1.1000E+04	1.3140E-02	1.7595E-02	1.3895E+02	1.7621E+02
12	1.2000E+04	6.8554E-03	9.1793E-03	4.7354E+01	8.7996E+01
13	1.3000E+04	1.0491E-02	1.4048E-02	1.3360E+02	1.7763E+02
14	1.4000E+04	4.7088E-03	6.3051E-03	3.9202E+01	8.6618E+01
15	1.5000E+04	4.6475E-03	6.2231E-03	1.3356E+02	1.8436E+02

TOTAL HARMONIC DISTORTION = 2.9522E+01 PERCENT

Figure 7: THD comparison in logarithmic scale

6.2 Hardware Testing

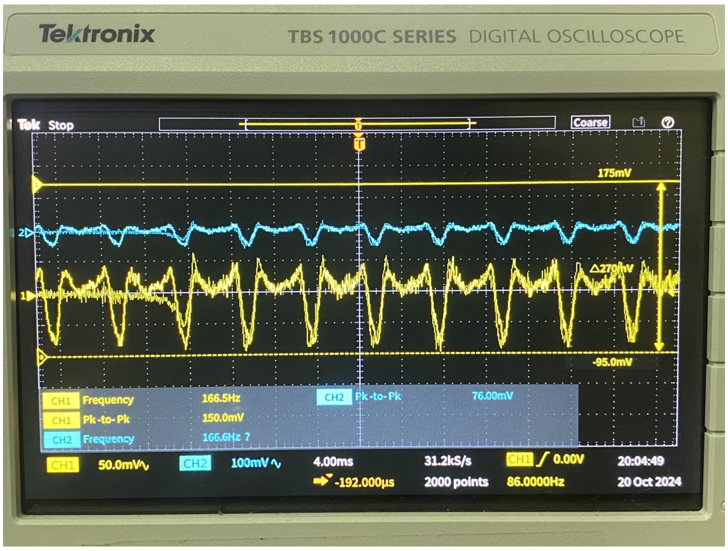


Figure 8: Amplified guitar signal at lowest gain setting

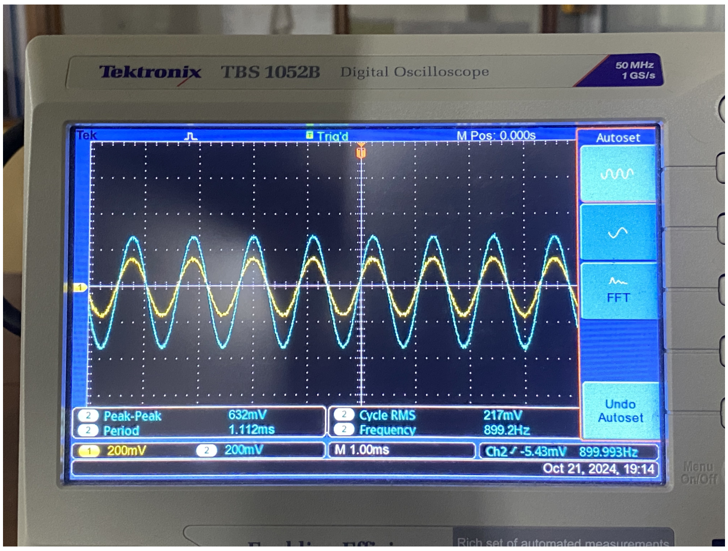


Figure 9: Amplified sinusoid signal at lowest gain setting

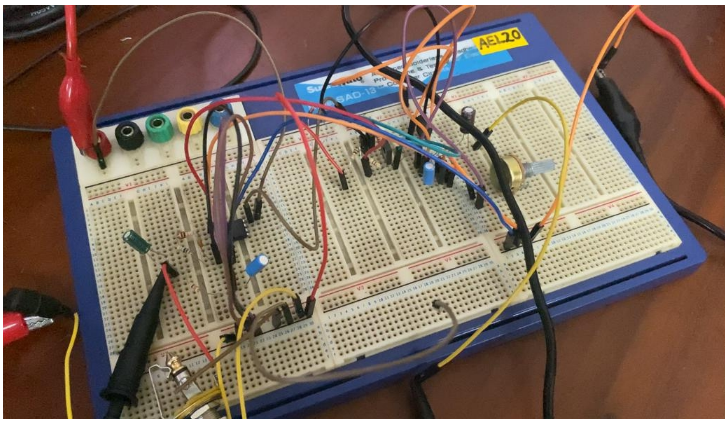


Figure 10: Breadboard implementation

7 PCB Design

We designed PCBs for our project using the ALTIUM Designer software and get it fabricated from JLCPCB, Hong Kong.

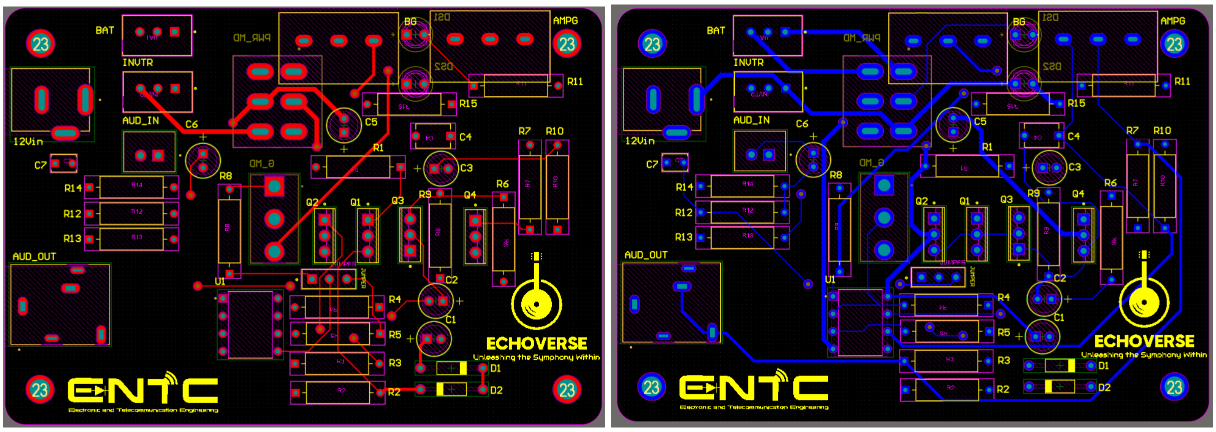
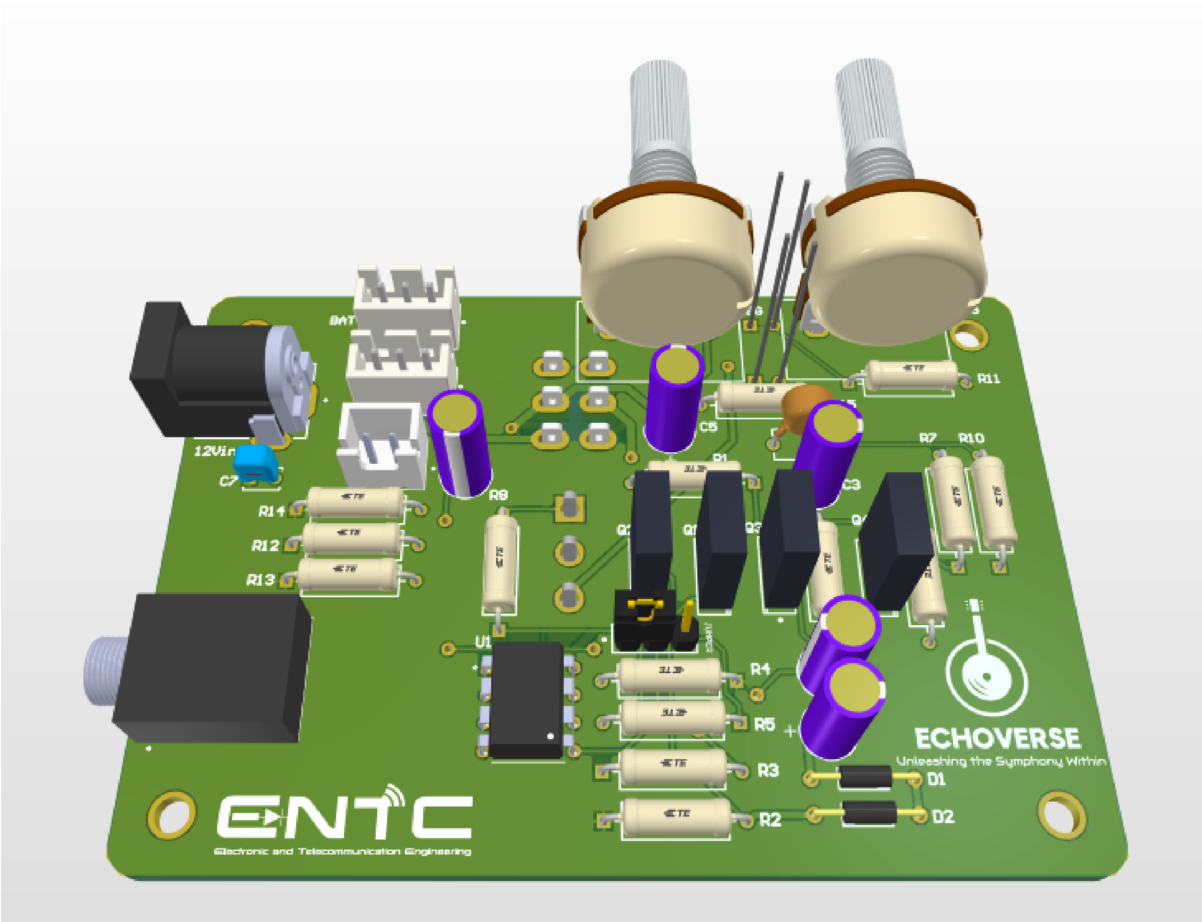


Figure 11: PCB Top and Bottom side Routing



3d view

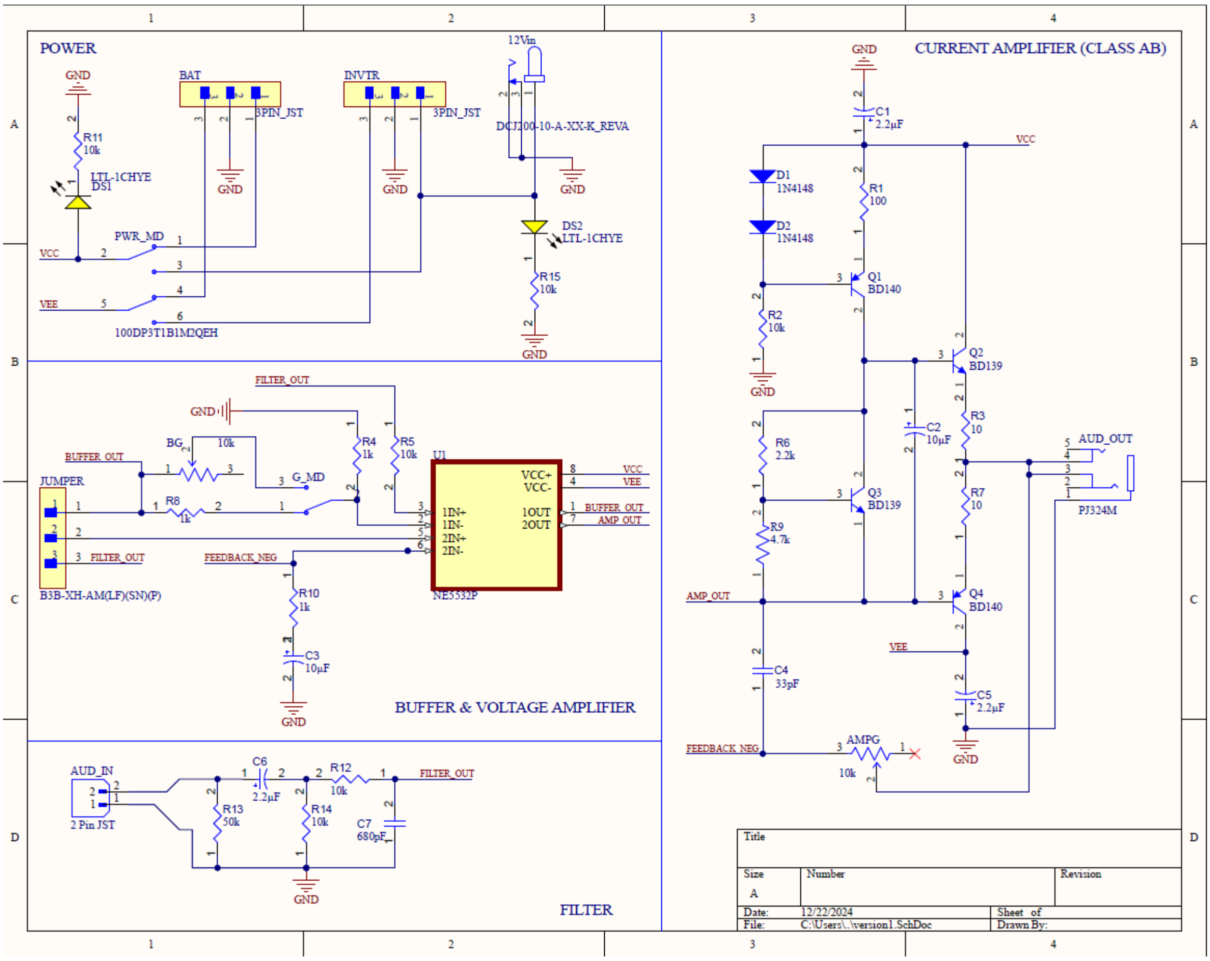


Figure 12: Implemented schematic

The PCB design prioritizes compactness and manufacturing efficiency, resulting in final dimensions of 86mm x 60mm—well within the 100mm x 100mm size constraint for optimal production costs and capability of fitting inside a small portable enclosure. The board utilizes a comprehensive ground plane strategy, with both top and bottom layers featuring full copper polygons connected to the ground net. This design choice enhances thermal management, provides low-impedance return paths, and minimizes electromagnetic interference (EMI) and ground loops also while providing ease of routing.

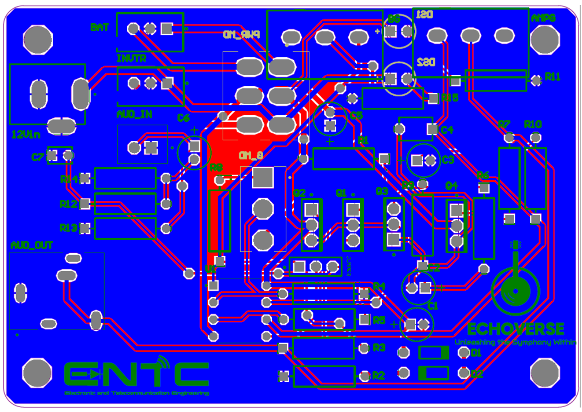


Figure 13: PCB with all layers and polygons

Critical attention was paid to trace widths throughout the design, with selective thickness modifications based on current requirements and signal integrity considerations. Power-carrying traces were appropriately sized to handle maximum current loads, while signal traces were optimized for noise immunity and impedance control. This meticulous approach to trace geometry ensures reliable operation while maintaining the board's compact form factor and manufacturability.

8 Enclosure Design

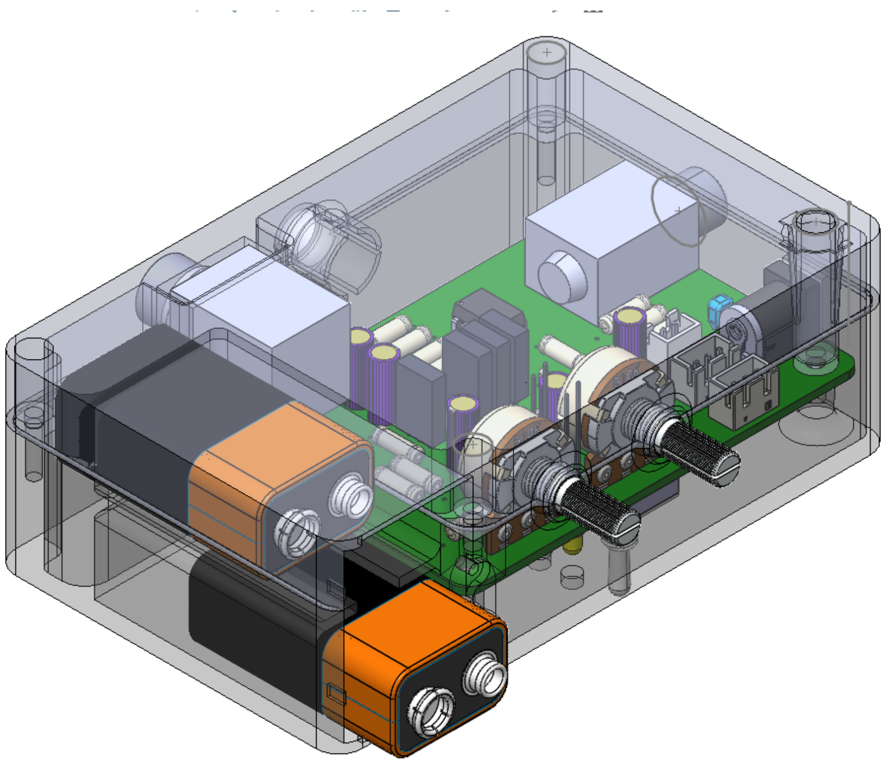


Figure 14: Final design

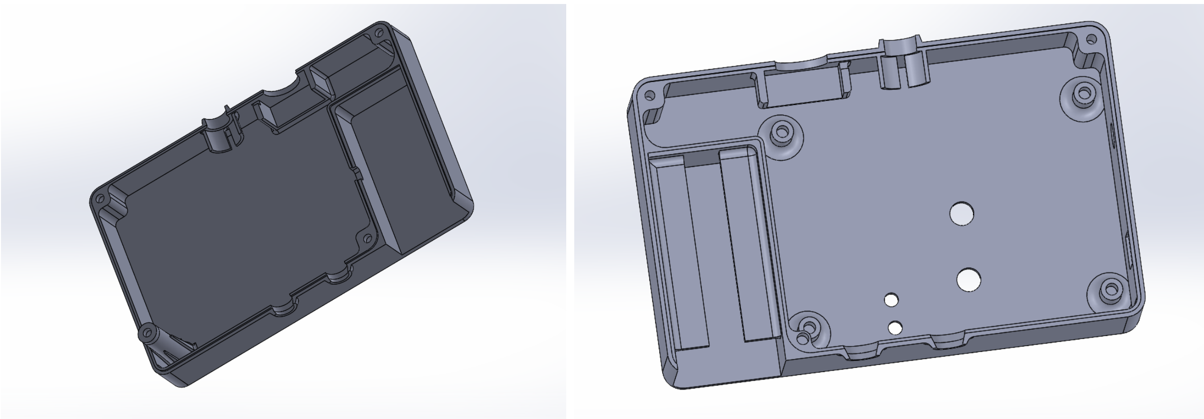


Figure 15: Top and bottom sections

9 Conclusion & Future Works

The Guitar Headphone Amplifier successfully delivers noise-free audio output in both headphone and speaker modes, meeting its core design objectives. However, during the transition from breadboard prototype to final PCB implementation, an unforeseen compatibility issue arose with the 1/8" stereo output socket. While the initial testing was conducted with a different socket model, the component selected for the final design exhibited intermittent connection issues. A temporary solution was implemented by routing the output through external wiring to a compatible audio socket, ensuring operational functionality. This component mismatch requires attention in future revisions to integrate a properly verified output socket directly on the PCB.

Additionally, comprehensive testing needs to be carried out to establish definitive specifications for maximum power output capabilities and speaker compatibility in speaker mode. These parameters need to be thoroughly characterized to provide users with accurate operational guidelines and ensure safe, optimal performance across various speaker configurations.
Also, for the external power supply mode, we have purchased an external inverting boost-converter circuit module. Once the module arrives, Tests need to be carried out to determine whether our device functions as intended in the external power supply mode.

In every phase of this project, we focused on maximizing the features and capabilities to ensure that every resource and investment was utilized to its fullest potential. Even though a simpler design could have achieved the core functionality, we consistently aimed to add value and deliver a comprehensive solution, making every effort and expense worthwhile.

10 Bill Of Materials

Item	Quantity	Reference	Part	Name
1	3	C1, C5, c6	2.2u	Capacitor
2	2	C2, c3	10u	Capacitor
3	1	C4	33p	Capacitor
4	1	C7	680p	Capacitor
5	2	D1, D2	1N4148	Diode
6	2	Q1, Q4	BD140	PNP Transistor
7	2	Q2, Q3	BD139	NPN Transistor
8	6	R(2, 5, 11, 12, 14, 15)	10k	Resistor
9	1	R6	2.2k	Resistor
10	3	R4, R8, R10	1k	Resistor
11	1	R13	50k	Resistor
12	1	R9	4.7k	Resistor
13	1		1	Resistor
14	2	R3, R7	10	Resistor
15	1	R1	100	Resistor
16	2	BG, AMPG	10K	Potentiometer
17	1	U1	NE5532	Operational Amplifier
18	2	DS1, DS2	LTL-1CHYE	LED
19	2	BAT, INVTR	-	3-pin JST
20	1	AUD_IN	-	2-pin JST
21	1	12Vin	DCJ200-10	DC Power jack
22	1	AUD_OUT	PJ324M	Stereo Headphone socket
23	1	-	-	1/4" mono audio jack
24	1	-	-	1/4" mono audio socket
25	1	-	-	3 pin header with jumper

11 Task Allocation

Index	Name	Task
220197E	GUNATHILAKA KL	PCB Design, Final Report, Soldering
220097X	DE ALWIS WMR	Presentation, Soldering, Testing & Debugging
220212A	HAPUARACHCHI HADND	Circuit Design, Simulations, Final Report, Soldering
220221B	HATHURUSINGHA HAR	Enclosure Design, Soldering

Table 4: Task Allocation Table

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