**Circuit Design – Fixed Challenge 2019**

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# Circuit design – Fixed Challenge 2019

## Overview of the Circuit

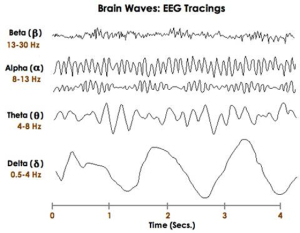
PolyCortex is a neurotechnology student organization that partakes in the NeuroTechX Fixed and Open Challenge competitions. The electronic team tasked with designing the circuit and PCB for the acquisition of EEG signal (Fixed Challenge) works alongside the informatic team in charge of programming an interface to visualize the signal.

The circuit PolyCortex has design for this year’s fixed challenge is detailed in this document. It is composed of 4 separate channels that can be wired to electrodes. Each channel includes filtering components (common mode chokes, RF filters), instrumentation amplifiers, various filters (high pass, low pass and notch) and a final amplification stage. Once the signal is treated and amplified, it is directed to the ADC which converts the signal from analog to digital in order to be forwarded to the interface for visualization. The circuit is powered by a 9V battery. However, the ADC is powered by ±2.5V obtained with DC-to-DC converters included in the circuit. To insure the grounding standard of the board, a right leg driver (RLD) circuit configuration has been added to the board. Lastly, the subject wearing the electrodes is protected by a transient voltage suppressor (TVS).

The conception of the circuit was simulated with LTspice and implemented in the DipTrace software, which allows the creation of a schematic and layout of the PCB. It was printed by Labo Circuits Inc. and the components ordered from Digi-Key Electronics were welded by PolyCortex’s electronic team.

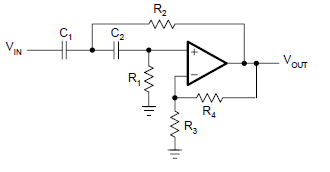
## Filtering

Due to their weak amplitudes, EEG signals are very susceptible to electromagnetic and common mode contamination. Additionally, EEG signals collected with electrodes may contain EMG information from the subject’s muscular activity and ECG signals from the polarizing cycles of heart cells. Is it thus important to filter the signal to isolate the frequency bands of interests for EEG analysis. The electroencephalogram is composed of 4 district waves ranging between 0.5 and 30Hz; the beta wave (13-30Hz), the alpha waves (8-13Hz), the theta waves (4-8Hz) and the delta waves (0.5-4Hz). PolyCortex therefore decided to filter outside of a bandwidth ranging from 0.3 to 35Hz to preserve all relevant EEG information.



*Figure 1 : Frequencies of EEG waves*

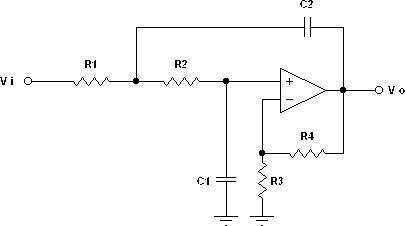
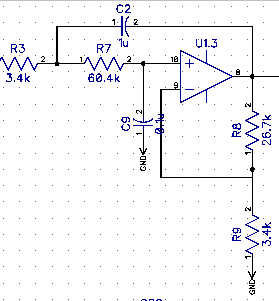
### High pass

The first filtering stage is a high pass Butterworth filter of the second order. The cutoff frequency f of such a filter is determined by the value of R2 and the value of C1 following the equation f =√2/(4\*π\*C\_1\*R\_2 ) with R\_1=2\* R\_2 and C\_1= C\_2. PolyCortex has chosen R1 = 75kΩ, R2 =37.4kΩ and C1 = C2 = 10µF, thus providing a cutoff frequency of 0.3Hz. The remaining resistor provide a gain to the filter, as explained in the Circuit Amplification section.

*Figure 2 : High pass filter configuration (left : DipTrace schematic, right: theorical configuration)*

### Low pass

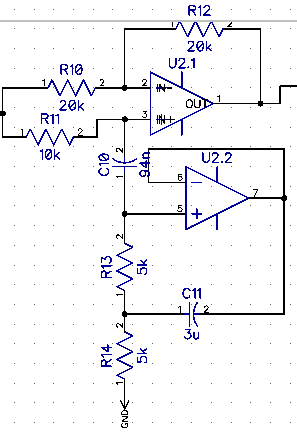
To insure the cutting off of EMG signals and other noise, the Butterworth low pass filter has a cutoff frequency of 35Hz. The cutoff frequency of this filter is given by the following equation referring to the right-side image of figure 5. In PolyCortex’s schematics (left-side of figure 5), these values have been set to R1 = 3.4Ωk, R2=60.4Ωk, C1= 0.1µF and C2= 1µF. Therefore, the cutoff frequency is 35Hz.



*Figure 3 : Low pass filter configuration (left : DipTrace schematic, right: theorical configuration)*

### Notch

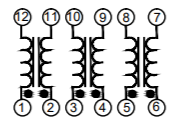
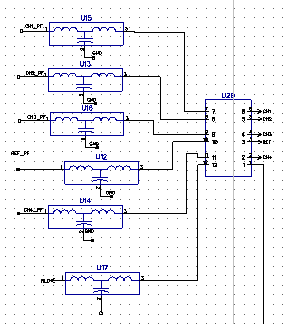
When working near electrical power-lines, the electronic circuits will be affected by the mains hum, or electric hum, which is a noise associated with the alternating current of the power-line. In PolyCortex’s case, the fundamental frequency of the mains hum is 60Hz coming from Hydro-Quebec and has a maximum intensity of 30dB. It was considered wise to add a notch filter to the circuit to target this specific intense noise. For this specific configuration, the cutoff frequency is given by the equation with and (referring to the right-side of figure 6). To obtain a cutoff frequency centered around 60Hz with a gain of at least -30dB to eliminate the mains hum, PolyCortex chose values of R1 = R2 = 5Ωk, R3 = 10Ωk, R4 = R5 = 20Ωk, C1 = 94nF and C2 = 3 µF. These values produce a gain of about -36dB when simulated in LTspice (see simulation section).



*Figure 4 : DipTrace schematic for the notch filter (cut-off frequency of 60Hz)*

### Common mode chokes

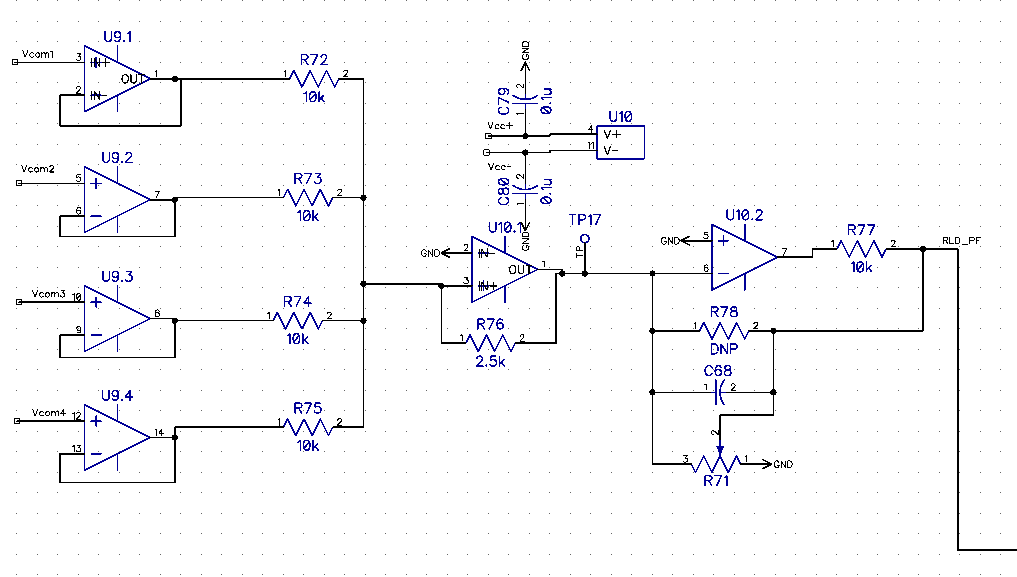
The circuit includes common mode chokes to eliminate a maximum of electromagnetic and radio frequency interferences from the power supply lines. The common-mode current creates a magnetic field when passing through the coil that opposes any increase of its intensity, thus blocking the common-mode current and passing differential current. PolyCortex chose CM4732V301R-10 by LAIRD, which works at a maximum current of 8,000mA and 30V.



*Figure 5 : DipTrace schematic of common mode chokes (left) and equivalent circuit (right)*

### Right leg driver

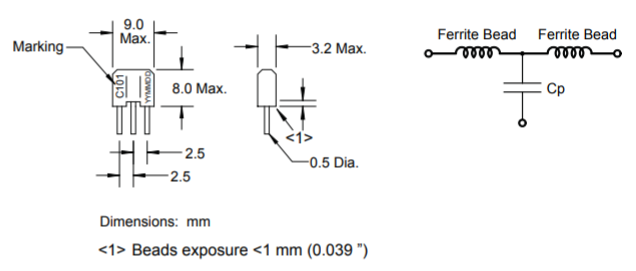
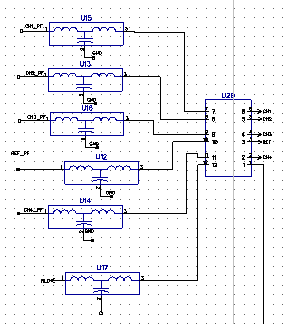
According to Texas Instruments, the common-mode rejection (CRM) is one of the most important parameters in ECG and EEG systems. Therefore, a right leg driver (RLD) circuit was added to further decrease the common-mode interference. The RLD circuit sets the user’s common-mode voltage to increase the effective common-mode rejection ratio of the circuit and low-passes the common-mode voltage measured by the differential amplification stage. This method provides a grounding standard by preventing the lost of voltage due to the difference in impedance between the ground electrode on the subject and the circuit itself.



*Figure 6 : Schematic for right leg driver*

### RF filters

Radio frequency (RF) filters were added to the circuit to remove high frequency (MHz-GHz) signals originating from broadcast and wireless communication. The filtering of these frequencies is important considering they could affect the envelop of the output signal. PolyCortex uses Bourns Inc.’s EMI103T-RC filter for their good noise filtering properties, which also attenuate the mains hum with a factor of about -50dB.



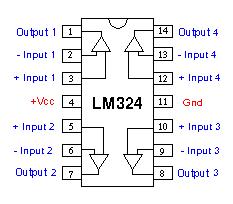
*Figure 7 : Configuration of RF filter (left : DipTrace schematic, right : functional diagram)*

## Amplification

Electrical signals coming from the human body have weak amplitudes typically ranging from 1mV to 100mV. For the electroencephalogram (EEG), the voltage that can be measured at the surface of the brain is about 1-2mV whereas it decreases to microvolts (μV) when measured on the scalp with electrodes.[[1]](#footnote-1) Thus acquiring and visualizing EEG signals requires amplification of ~ 5 000. Such a gain allows the manipulation of the signals without saturating the operational amplifiers present in the circuit.

### Operational amplifier

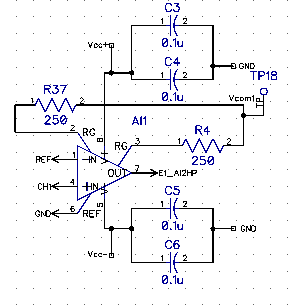
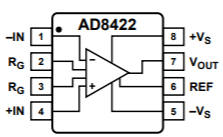
The op-amps used in the circuits are Texas Instruments’ trusted LM324. They were chosen for their built-in 4 operational amplifiers, their supply range of 3.0 to 32V and their typical common-mode rejection of -120dB.



*Figure 8 : functional diagram of LM324 amp-op*

### Instrumentation Amplifier

The circuit to acquire EEG signals contain an operational amplifier placed directly after the electrodes to provide the signal with an initial gain before being filtered. The op amp used is Analog Devices’ AD8422, which is a high performance, low power, rail-to-rail precision amplifier. For the AD8422, the gain is determined by placing a single resistance RG across pin 2 and 3. PolyCortex decides the value of this resistance would be 2 times 250Ω, therefore inducing a gain of 40.6 (Gain = 1 + 19.8kΩ/RG). Furthermore, the datasheet suggests placing bypass capacitors (C3, C4, C5 and C6) as close as possible to each supply pins.

*Figure 9 : DipTrace Schematic and connection diagram of the in-op AD8422*

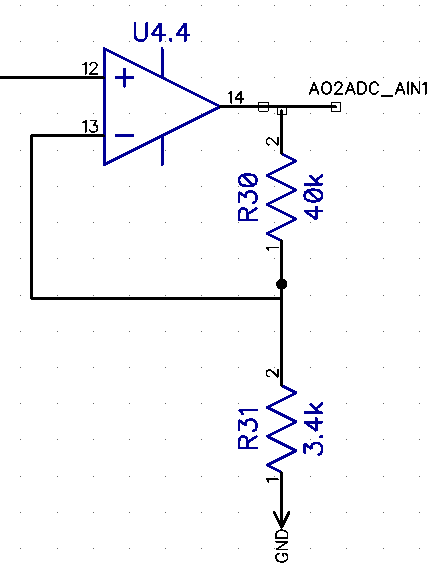
### Circuit Amplification

To obtain the expected gain of ~5 000, the different filtering layers can also be used to introduce a gain. The filters used in this EEG circuit are second order Butterworth active filters where two resistors (Rf and Ri) , R18 and R19 on figure 2, can be connected to the output signal without affecting the cutoff frequency. Consequently, the gain of the high pass and low pass filter is proportional to the ratio of these two resistors (Gain = 1 + Rf/Ri). During the design process, PolyCortex chose to introduce a gain of 8.9 in both filtering levels.



*Figure 10 : High pass filter with a gain (G = 1 + R18/R19) of 8.9*

After the signal has made its way through the amp-op and the filtering levels, it is amplified a final time with a non-inverting operational amplifier. For this configuration, the gain is once more proportional to the ratio of the chosen resistors (Gain = 1 + Rf/Ri) R30 and R31 on figure 3.



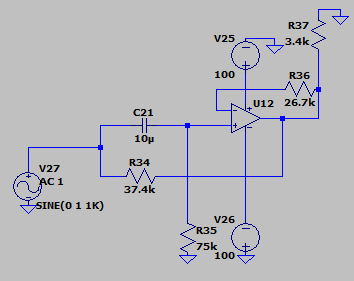
*Figure 11 : Final amplification level with a gain of 12.8 (G = 1 + R30/R31)*

The total gain produced by the cascading of the amp-op, the high pass and low pass filter and the non-inverter is thereby the multiplication of each individual gain, producing a final gain of ~41100.

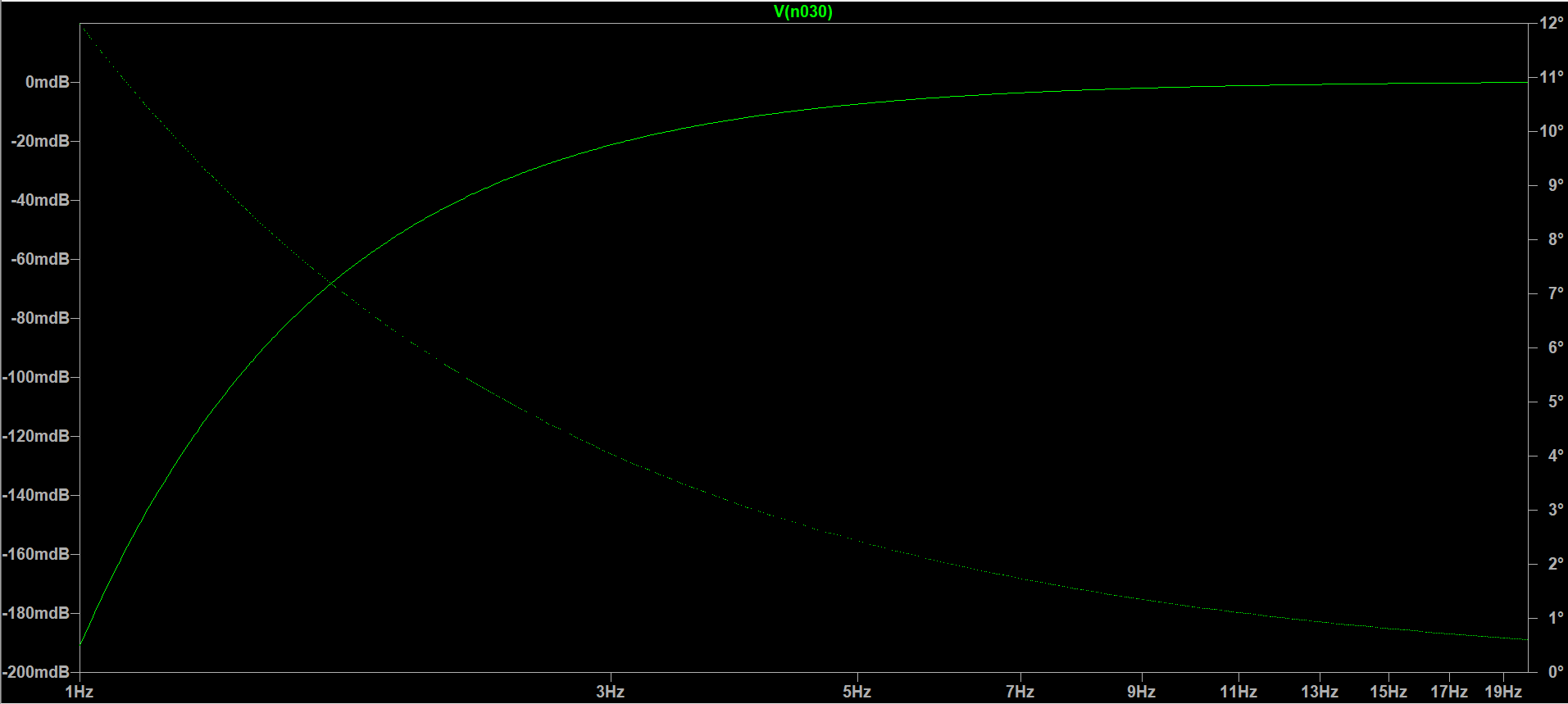
## Simulation

To insure the circuit behaves like it should, PolyCortex simulated every filtering stages with LTspice and tested the final amplification as well as the filtering capacities. In order to test the filters, a AC Analysis with 100 steps per decade, a start frequency of 1Hz and a stop frequency of 200Hz. This kind of analysis allows the visualizing of the circuit’s frequency response between the start and stop frequency and displays the Bode plot.

### High pass filter

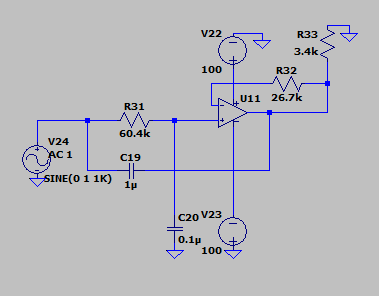


*Figure 12 : LTspice schematic of the high pass filter*

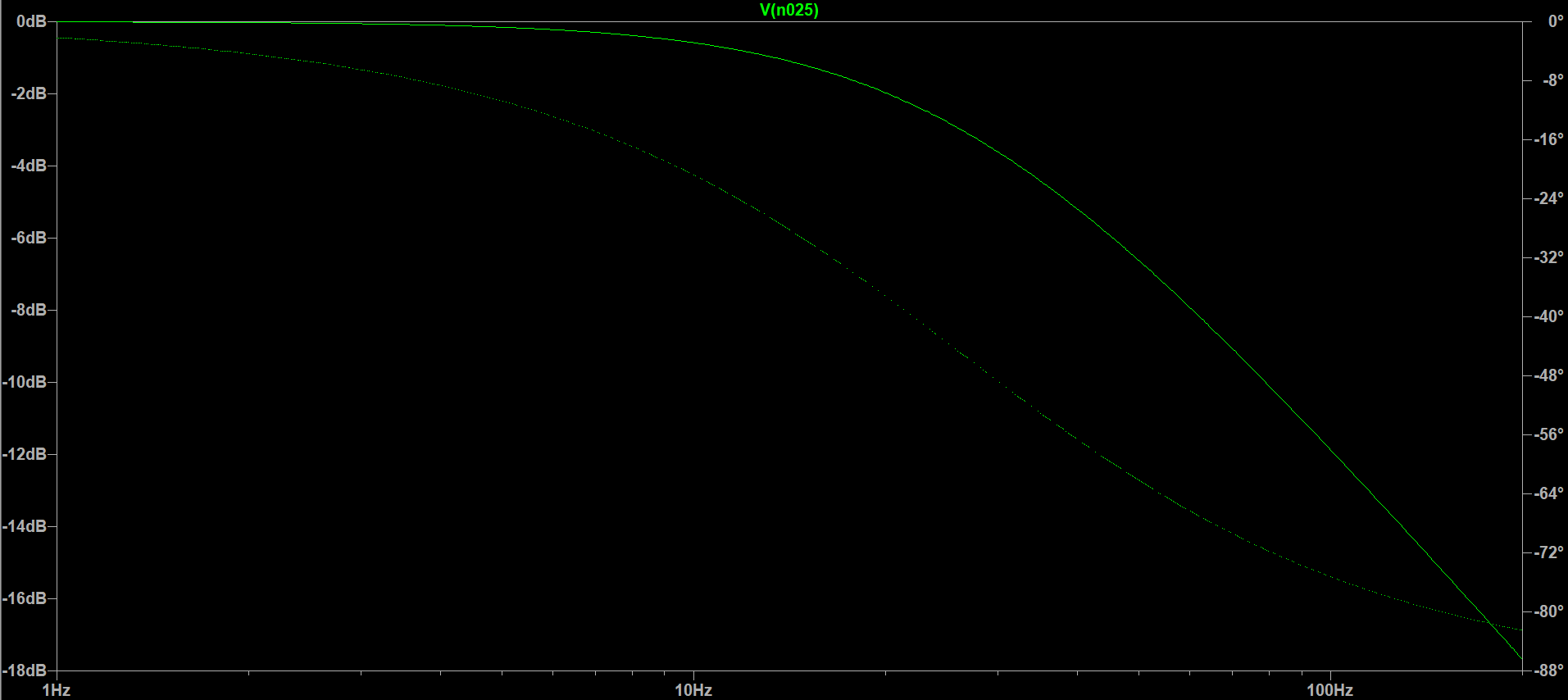


*Figure 13 : Bode plot of high pass filter with a cutoff frequency of 0.3Hz*

### Low pass filter

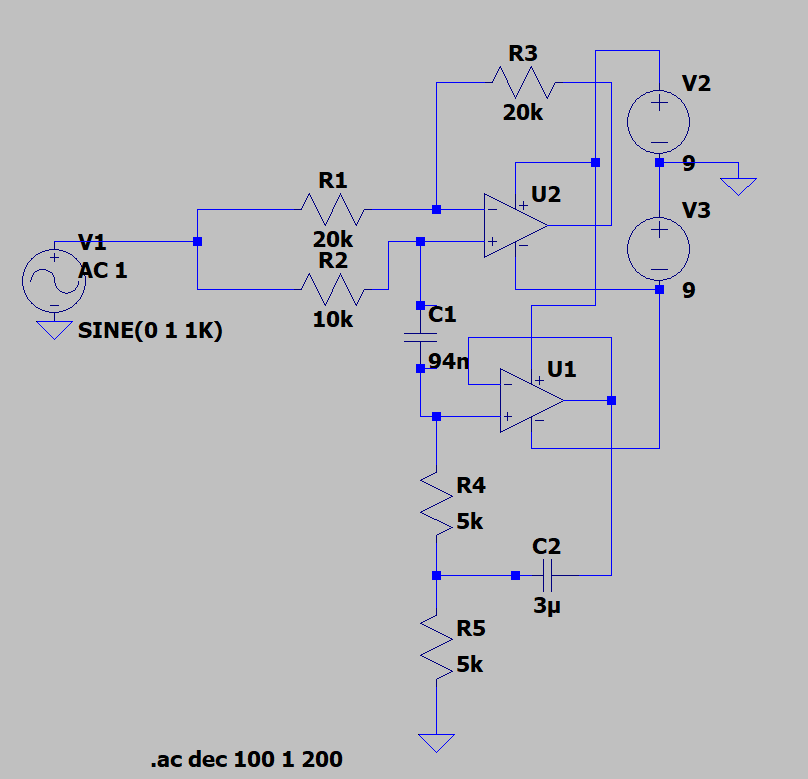


*Figure 14 : LTSpice schematic of low pass filter*

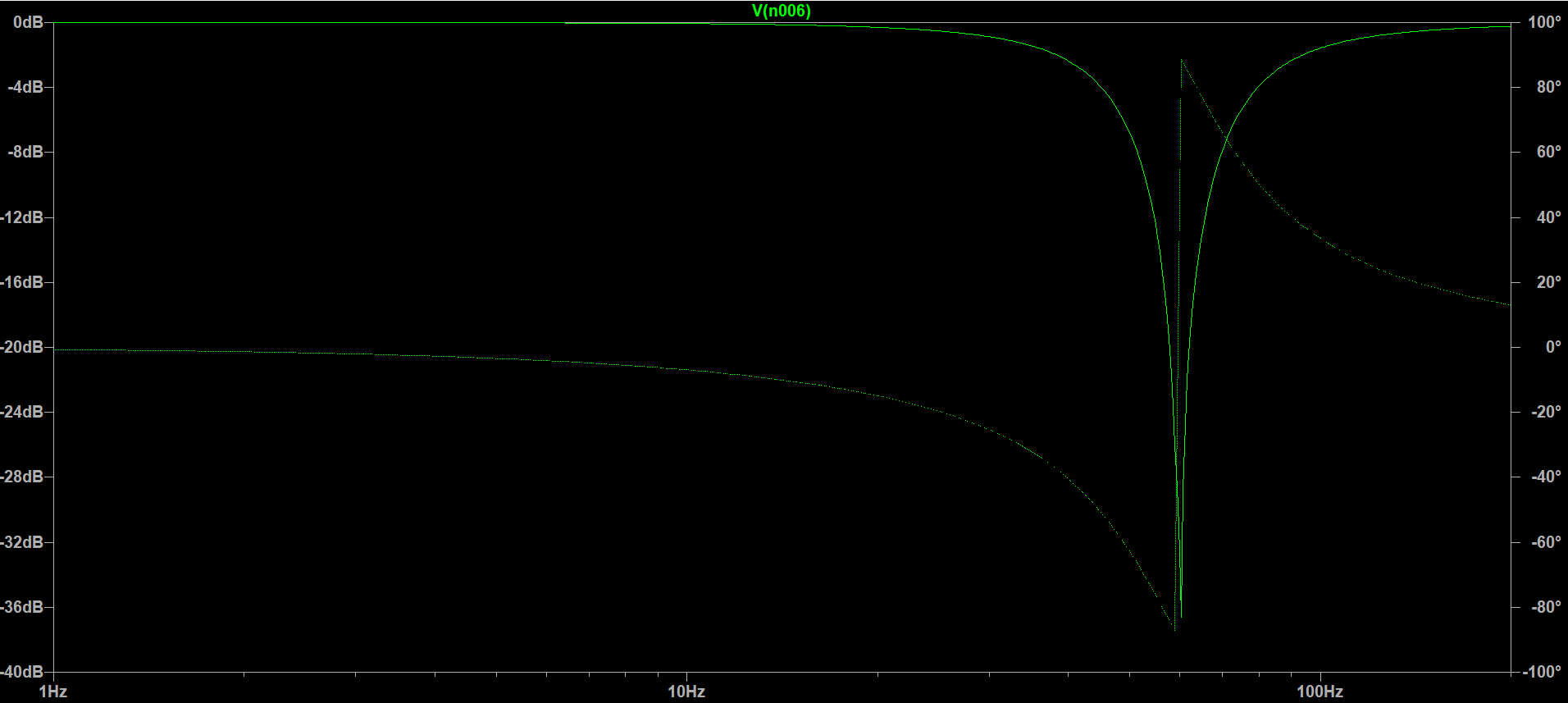


*Figure 15 : Bode plot of low pass filter with a cut off frequency of 35Hz*

### Notch

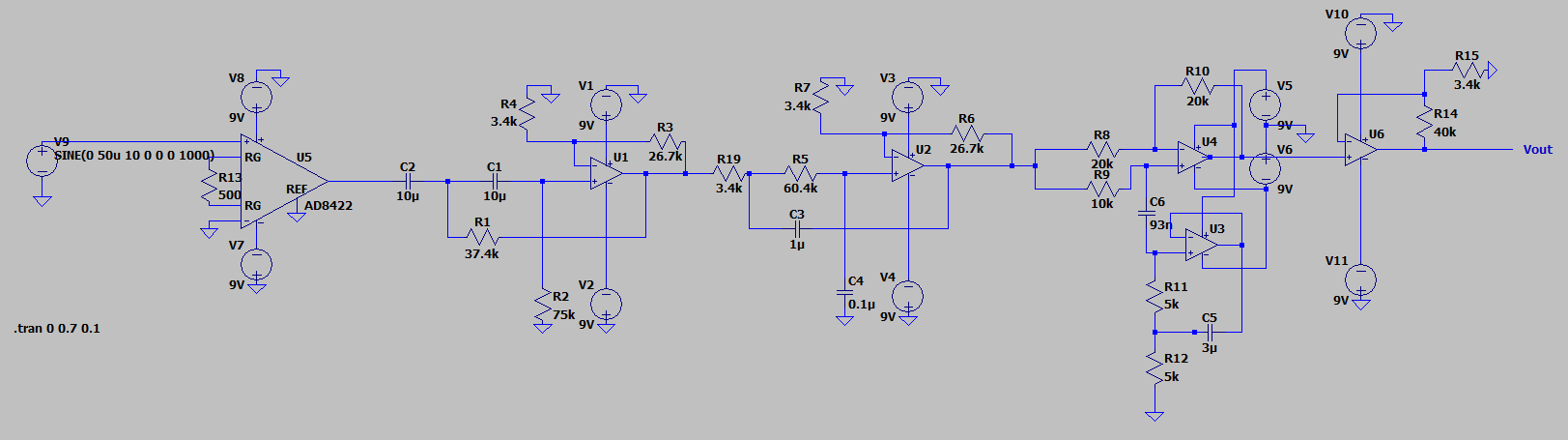


*Figure 16 : LTspice schematic of notch filter*

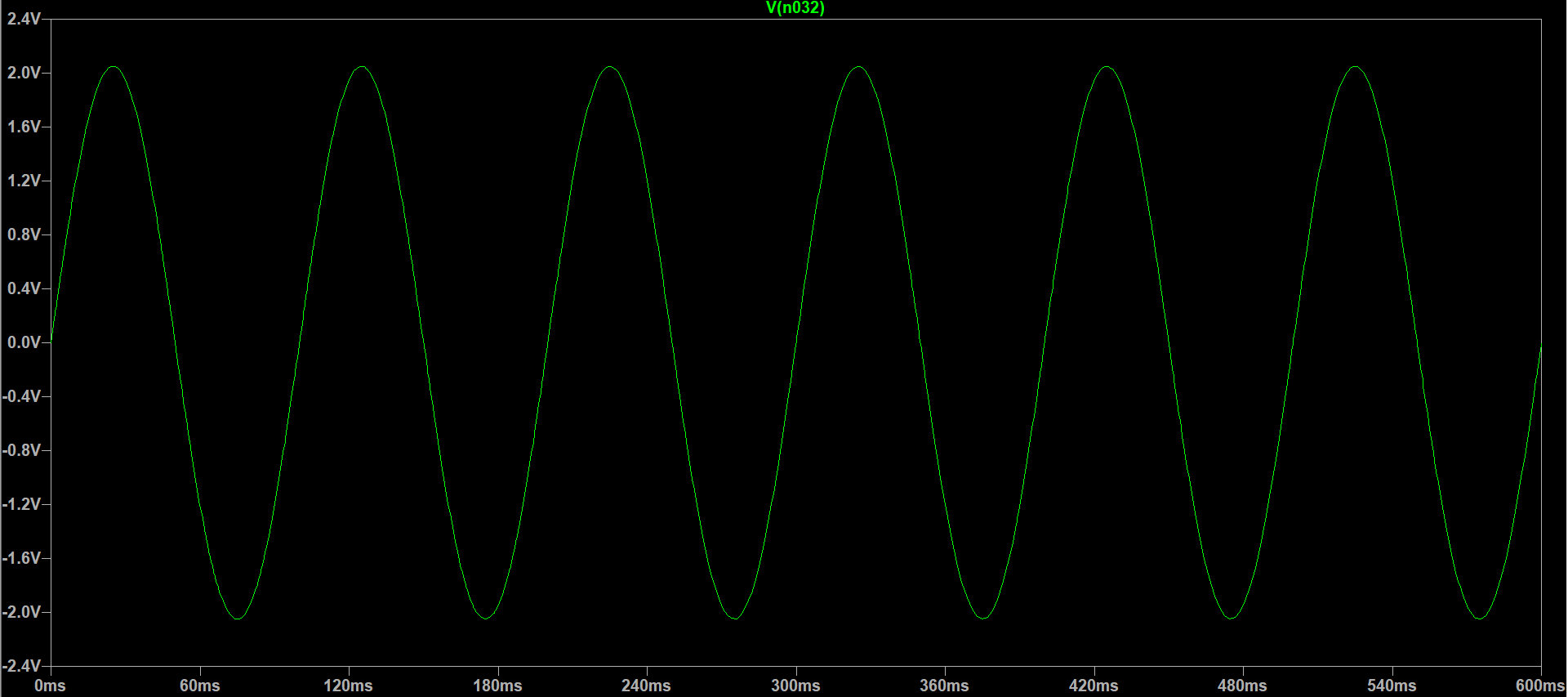


*Figure 17 : Bode plot of notch filter with a center frequency of 60Hz*

### Complete circuit for 1 channel

To test the complete circuit of a channel, the Transient analysis was used with a stop time of 0.7 seconds. Such an analysis allows the visualisation of the non linear transition response of the circuit in the temporal domain, much like an oscilloscope would. The input signal is a sin wave with an amplitude of 50µV and a frequency of 10Hz. As seen in figure 19, the output signal as an amplitude of ~2.05V, indicating a gain of ~41000.

*Figure 18 : LTspice schematic of complete circuit of 1 channel*



*Figure 19 : Output signal of complete circuit of 1 channel*

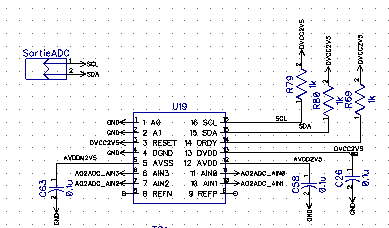
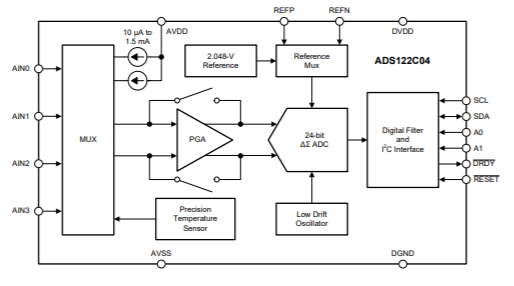
## Other Components

### Power supply

In previous version of the EEG acquisition circuit, the amp-ops were supplied with 5V and saturation was observed while gathering EEG data. Instead of decreasing the overall gain of the circuit, PolyCortex decided to increase the power supplying the circuit. The Vcc+ net of the circuit was thus set to 9V and the Vcc- to -9V since the board is powered with 9V batteries.

### ADC

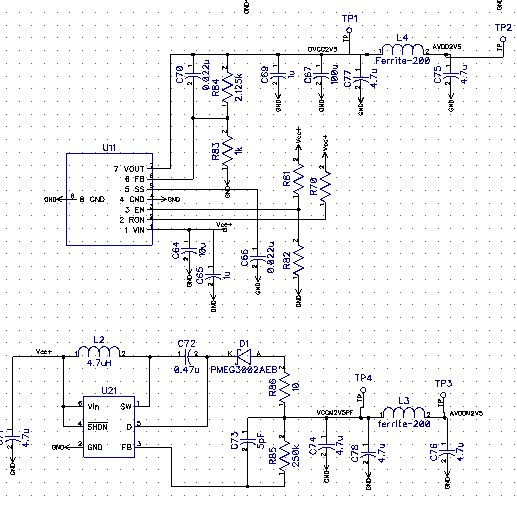
The PCB created to acquire the EEG waves is made to be plugged into an interface to visualize the signals. To insure the communication between the circuit and the interface’s program, the voltage of the four channels must be converted from analog to digital. Texas Instruments’ 24-bit ADS122C04 was selected for its 4-channel input, its high sampling rate of 2kSPS. Furthermore, this ADC uses the Delta-sigma analog-to-digital converting method, which pushes the noise to higher frequency in order to increase its resolution. This ADC also helps eliminate common-mode noise by providing a typical CMRR of 110dB for a frequency of 60Hz (with DR=2kSPS).

*Figure 20 : DipTrace schematic of the ADS122C04 ADC and functional diagram*

### DC-to-DC converters

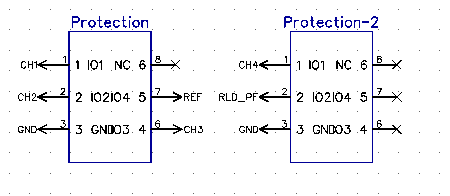
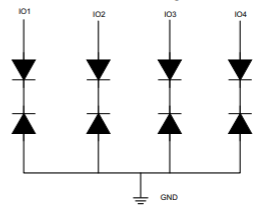
The ADC require ±2.5V analog and digital supply to function. Therefore, a LT3483IS6 and a LMZ12002TZ DC-to-DC converter were added to the circuit in order to transform the 9V from the battery to ±2.5V while also regulating the voltage input of the ADC. The LT3483 is commonly used to produce analog negative voltage outputs, while the LMZ12002TZ is used to carry out analog and digital output. Both were chosen for their input range (2.5V to 16V for LT3483IS6 and 4.5V to 20V for LMZ12002TZ) which largely accommodate the 9V of the battery and their voltage output (-2.5V to -38V for LT3483IS6 and 0.8V to 6V for LMZ12002TZ) suitable to power the ADC.



*Figure 21 : DipTrace schematic of DC-to-DC converter (top : LMZ12002TZ, bottom : LT3483IS6)*

### Protections

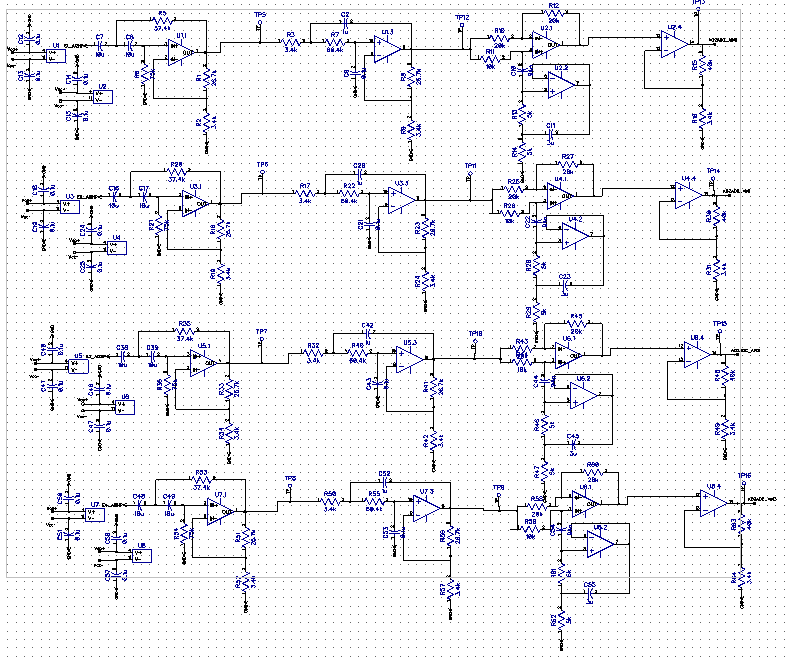
Since PolyCortex will be testing the board on a human being to acquire their EEG signals, it was considered wise to add a circuit protection component between the electrodes and the beginning of the circuit. Texas Instruments’ TPD4E1B06DCKR 4-channel bi-directional Transient Voltage Suppressor (TVS) diode array was chosen for its low leakage current (0.5nA) which insure the precision of analog measurements. It offers protection for currents exceeding 3.0A (8/20µS).

*Figure 22 : DipTrace schematic of protection circuit TPD4E1B06DCKR and functional diagram*

## Schematic, layout and routing

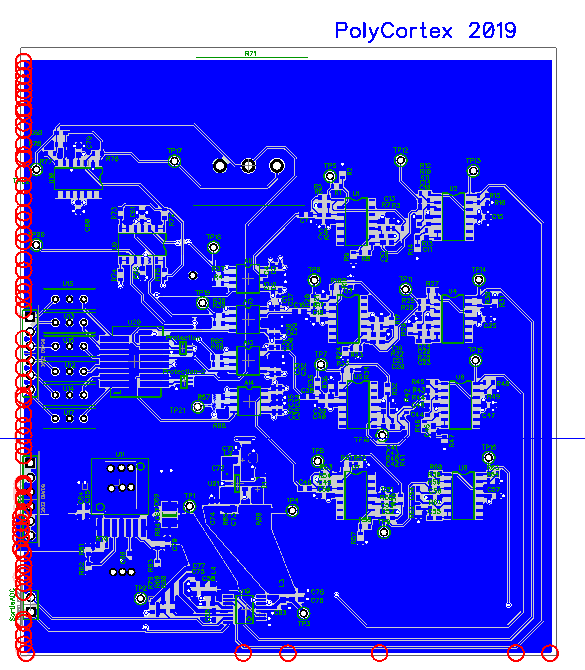
Before the PCB can be printed out, the circuit must be built on a schematic. Then, the schematic is converted to a PCB, where the components must be placed and routed to one another. These steps were executed with the DipTrace software, which offers a schematic capture editor, a PCB layout editor, a component editor and a pattern editor module. The component and pattern editor tools are used to incorporate custom component that might not be included in DipTrace libraries.



*Figure 23 : DipTrace schematic for 4-channel circuit*

The PCB PolyCortex created has 4 layers : the top one contains the pads on which the components are wielded and wires, the middle layers consists of the ground and power supply, and the bottom layer contains additional wiring. A copper plating was placed on top to surround the components and wires to further isolated them and reduce parasitic interference between the channels.

When doing the layout, PolyCortex took into consideration the size of the board, which could not exceed 15cm by 15cm, and the proximity of the components. The components were placed as close to each other as possible to minimize signal quality degradation. Furthermore, the analog and digital components were separated to avoid interference. While routing the circuit, the 90° angles were carefully avoided to prevent current concentration. Long parallel wire line were also avoided to stop parasitic impedance from containing the signals.



*Figure 24 : DipTrace layout of the finished PCB*

The completed PCB was exported in *gerber* files and sent to Labo Circuits Inc. for printing.

## Testing

Test the circuit by connecting a sinusoidal signal with a waveform generator at the minimal tension (i.e. 20 mV) and at a frequency of 20 Hz. Connect the positive terminal of the waveform generator to the electrode 1 (on the “Electrodes” header) and the negative terminal to the reference electrode (on the “Electrodes header). Connect with femalefemale wires the GND and the Vcc (on the “Supply” header) to the 9V battery. Connect the negative terminal of an oscilloscope to the GND and the positive terminal to the “E1” electrode (on the “SortieADC” header). A square signal at 20 Hz should appear. Because the lowest amplitude generated by the instrument is much higher than an EEG signal (20 mV >> 100 µV), the output signal is saturated which explains the square form.

## Board cost

A list of the 207 components of the circuit is annexed to this document. The total cost of the component, which were ordered on Digi-Key Electronics, is 157,06 CAN$. The PCB was printed by Labo Circuits Inc. for a fix cost of 225 CAN$ and 57,16$ per copy. The board cost can therefore be evaluated to 282,16 CAN$. The total cost of the board with the component is 439,21 CAN$.

# Annexes

## Table 1 : List of component of the PCB

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Component** | **Value** | **Pattern** | **Quantity** | **$/u** | **Total $** |
| ADC | - | ADS122C04 | 1 | 9,93 | 9,93 |
| Capacitor | 0.1u | CAP\_0603 | 43 | 0,0558 | 2,3994 |
| Capacitor | 1u | CAP\_0603 | 6 | 0,15 | 0,9 |
| Capacitor | 10u | CAP\_0603 | 9 | 0,21 | 1,89 |
| Capacitor | 0.12u | CAP\_0603 | 4 | 0,33 | 1,32 |
| Capacitor | 2.2u | CAP\_0603 | 4 | 0,154 | 0,616 |
| Capacitor | 0.022u | CAP\_0603 | 2 | 0,073 | 0,146 |
| Capacitor | 100u | CAP\_1210 | 1 | 0,949 | 0,949 |
| Capacitor | 4.7u | CAP\_0603 | 6 | 0,15 | 0,9 |
| Capacitor | 0.47u | CAP\_0603 | 1 | 0,12 | 0,12 |
| Capacitor | 5pF | CAP\_0603 | 1 | 0,061 | 0,061 |
| Common mode choke | - | CM4732V301R-10 | 1 | 4,43 | 4,43 |
| CON | - | CON6M | 14 | 0,068 | 0,94 |
| DCDC Converter | - | LMZ12002 | 1 | 7,69 | 7,69 |
| DCDC Converter | - | LT3483IS6 | 1 | 6,81 | 6,81 |
| Diode | - | PMEG3002AEB | 1 | 0,49 | 0,49 |
| Inductance | 4.7uH | LQH2MCN100K02L | 1 | 0,38 | 0,38 |
| Inductance | - | Ferrite-200 | 2 | 0,079 | 0,158 |
| Instrumentation amp | - | AD8422 | 4 | 8,81 | 35,24 |
| Operational amp | - | LM324 | 10 | 0,295 | 2,95 |
| Potentiometer | 500-1M | 201XR | 1 | 0,79 | 0,79 |
| Protection | - | TPD4E1B0 | 2 | 0,736 | 1,472 |
| Resistor | 26.7k | RES\_0603 | 8 | 0,53 | 4,24 |
| Resistor | 3.4k | RES\_0603 | 16 | 0,53 | 8,48 |
| Resistor | 250 | RES\_0603 | 8 | 2,15 | 17,2 |
| Resistor | 37.4k | RES\_0603 | 4 | 0,15 | 0,6 |
| Resistor | 75k | RES\_0603 | 4 | 1 | 4 |
| Resistor | 60.4k | RES\_0603 | 4 | 0,53 | 2,12 |
| Resistor | 20k | RES\_0603 | 8 | 0,1172 | 0,9376 |
| Resistor | 10k | RES\_0603 | 9 | 0,15 | 1,35 |
| Resistor | 5k | RES\_0603 | 8 | 3,07 | 24,56 |
| Resistor | 40k | RES\_0603 | 4 | 0,839 | 3,356 |
| Resistor | 1k | RES\_0603 | 4 | 0,15 | 0,6 |
| Resistor | 32.4k | RES\_0603 | 2 | 0,1172 | 0,2344 |
| Resistor | 2.5k | RES\_0603 | 1 | 1,217 | 1,217 |
| Resistor | 11.8k | RES\_0603 | 1 | 0,3 | 0,3 |
| Resistor | 2.1k | RES\_0603 | 1 | 0,39 | 0,39 |
| Resistor | 250k | RES\_0603 | 1 | 0,8761 | 0,8761 |
| Resistor | 10 | RES\_0603 | 1 | 0,54 | 0,54 |
| RF Filter | - | EMI T filter | 6 | 0,483 | 2,898 |
| Supply battery | 9V | - | 1 | 2,572 | 2,572 |
| TOTAL |  |  | 207 |  | 157,06 |

# Reference

1. [↑](#footnote-ref-1)