A MINIATURE FOUR CHANNEL HEADSTAGE AMPLIFIER

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ABSTRACT
The design and construction of a miniature four-channel headstage amplifier for use with tetrodes is presented, including specification, response characteristics, schematics, printed circuit board layout, parts lists, and suppliers.

INTRODUCTION
Proper signal conditioning when making neural recordings requires a first stage of amplification and impedance transformation that is located physically close to the recording electrode. This requirement of proximity is primarily due to the relatively high source impedance of electrodes typically used for neural electrophysiology, as even short signal runs become subject to pickup from external sources. In turn, proximity requires miniaturization of the electronics, and when multi-channel electrodes are used, such as tetrodes, this requirement is compounded.

One standard solution to this problem is to use a single stage of impedance matching with a lone JFET follower. The advantages to this approach are low-power and extremely small size, while the disadvantages are higher noise levels, lack of gain and filtering, and lack of sufficient drive to power substantial cable runs. Trying to solve all of the design constraints with one transistor means compromising on nearly every aspect of circuit performance.

Therefore, the approach taken in this project was to use commercially available operational amplifiers in surface mount packages. While this has the disadvantage of being
substantially larger than some approaches (especially since, as will be discussed, components selected were far from the most compact available), it is still quite small, and has the advantage of being able to optimize input, transfer, and output characteristics. The result, as presented here, is a very low-noise, low-power, miniature four channel ac amplifier with second-order high-pass rolloff, that is robust and can drive a long cable with ease.

The design uses a small printed circuit board which holds all of the circuitry, directly connects on one end to a recording electrode, and at the other through a 5 meter cable to a secondary amplifier and power source. Without the cable and associated connector, the headstage measures approximately 15 mm by 60 mm and weighs some 10 grams. It accepts signals from high impedance electrodes, amplifies with a gain of 100, and filters with a highpass rolloff of 0.1 Hz and a low-pass rolloff of 15 kHz.

**Methods**

*Schematic and Design Description*

The schematic for the tetrode headstage amplifier (THA2) can be seen in Figure 2. Signals arriving at the input connector are filtered with a dc blocking capacitor and a bias-current bleed-off resistor forming a first-order high-pass filter, amplified by the first stage which has a first-order low-pass rolloff, and further amplified by the second stage, also with a first-order low-pass rolloff, before being driven into a long cable.

Because the source impedance from neural electrodes is typically 0.1–3 MΩ, and recorded voltages are on the order of tens to hundreds of microvolts, the current noise of the first stage of amplification is more important than its voltage noise. Further, to insure that bias currents from the amplifier do not affect the experimental subject, and to eliminate the wet cell voltage created by the electrode in tissue, a dc blocking capacitor is necessary, along with a bleed resistor to prevent bias currents from floating the input node into saturation. These two components are selected so that they form a high-pass filter with \( f_c = 0.1 \text{ Hz} \), a sufficiently low cutoff to retain signals of interest while providing the required isolation. The operational amplifier selected for this stage is National Semiconductor’s LM6082AIN; it has outstanding noise characteristics, low input bias current, good input offset voltage, reasonable power dissipation, and a reasonable gain-bandwidth product. It is used in a non-inverting configuration with a gain of 10, with a single low-pass zero inserted in the feedback path to reduce the gain to 1 for signals above 15 kHz. This feedback network also insures stability which is often a concern with these and similar low-noise, low-input current, fast amplifiers.

The second stage is optimized for driving cables, and thus, a higher output-current amplifier was chosen, and designed again in a non-inverting configuration with a single low-pass zero in the feedback path, reducing the nominal gain of 10 to a gain of 1 above 15 kHz. The operational amplifier selected for this stage is Linear Technology’s LT1355, a high output-current, wide-bandwidth, low-noise amplifier that consumes a reasonable amount of power.

To insure high-quality isolation, power is delivered to the headstage at ±8V and locally regulated to ±5V. The incoming power lines are decoupled via 4.7μF tantalum capacitors before regulation through an LM78L05 for the positive supply and an LM79L05 for
the negative supply. Each integrated circuit has local decoupling capacitors for both supplies, and the layout insures a low-impedance ground path. Local power regulation is important to prevent signals picked up in the power-supply leads from appearing in the opamp outputs; although the low-frequency power supply rejection of modern opamps is excellent, above 10 kHz or so, it can be as low as 20–40 dB.

The cable is driven from the second stage in a single-ended configuration, however, the cable has individual coax cables for each channel, and an overall shield. The signal ground is taken from the power supply ground and is kept separate from the overall shield. At the receiving end (not described in this document), the signal is differentially amplified for a pseudo-differential configuration, combining the better noise rejection of differential signaling, with the lower component count of single-ended signaling.

The overall shield is not made available at the electrode end of the headstage, but is brought out to the connector housing at the secondary amplifier end of the cable. At the secondary amplifier, it is connected to chassis ground. The combination of local power regulation, pseudo-differential signaling, and outer shield knocks external interference down to manageable levels, as presented below.

The primary use for these amplifiers is with four-wire electrodes called tetrodes (Pezaris, Sahani and Andersen, 1998). The input connector was selected to provide a direct connection to the previously developed carrier tubes, and is a four-position header with gold-plated contacts. The output connector is a 12-pin locking circular connector which, although somewhat expensive, is small, rugged, reliable, and dense. The cable was selected to provide the desired layers shielding while also being flexible, so as to limit strain applied to the input connector and therefore the attached electrode, and fit the output connector.

**PCB Layout**

A two-sided printed circuit board layout, 0.450 by 1.975 inches (11.4 by 50.2 mm) when cut, is shown in figure 2. Each side of the board holds two channels, and signal flow is routed cleanly from the input connector (on the left edge in figure 2) through to the output connector (on the right edge). Power is distributed through traces around the periphery, and ground along a central strip. Each longitudinal half of both sides is nearly symmetric, and the two sides are nearly identical, with the majority of the differences occurring at the local regulation near the cable soldering points. To minimize width and length and not require additional layers, a design was chosen which uses two jumpers, both at the local regulators, and both to transfer regulated power to the opposite side of the board.

**Parts List**

A list of required parts is given in Table 1. At the time of this writing, these parts are all readily available, and reasonably inexpensive. The author can be contacted for limited copies of the printed circuit board, or an excellent source for low-volume PCBs can be found in the sources section. Net lists and Gerber plots are available upon request for non-commercial use.
Figure 1: Headstage Schematic
Figure 2: PCB layout.
Layers used to construct printed circuit board, plotted at approximately twice life-size. Mask layers are presented in negative, and bottom layers in mirror image, as is standard for the industry. The rectangular outline represents the edge of the board, and actual size is 0.450 by 1.975 inches (approximately 11.4 by 50.2 mm). A, top mask. B, top etch. C, bottom etch. D, bottom mask.
item | part number | description | source  
--- | --- | --- | ---  
PC1 | THA1 (Custom) | printed circuit board | Advanced Circuits  
IC1, IC3 | LMC6082AIM | input stage opamp | Digi-Key  
IC2, IC4 | LT1355CS8 | output stage opamp | Digi-Key  
IC5 | LM78L05ACM | 5V positive regulator | Digi-Key  
IC6 | LM79L05ACM | 5V negative regulator | Digi-Key  
R11-R14 | RK73H2AT1005F | 0805 10M 1% Surface Mount Dist. |  
R21-R24, R41-R44 | P1005CCT | 0805 10k0 1% | Digi-Key  
R31-R34, R51-R54 | P9095CCT | 0805 90k9 1% | Digi-Key  
C01-C08 | ECJ-2YB1H104K | 0805 0.10uF 50V X7R | Digi-Key  
C11-C14 | ECJ-2YB1E224K | 0805 0.15uF 25V X7R | Digi-Key  
C21-C24, C31-C34 | ECU-V1H121JCG | 0805 120pF 50V NPO | Digi-Key  
C41-C42 | ECS-T1CY457R | EIA(A) 4.7µF 16V tantalum | Digi-Key  
W1 | 3M1181B-ND | shielding tape | Digi-Key  
W2 | EPS2034-1T5 | shrink tube | Digi-Key  
T1 | 929852-01-36T5 | input connector (modified) | Digi-Key  
T2 | HR10-10P-12P | output connector | Digi-Key  
X1 | GC397-ND | reference input clip lead | Digi-Key  
X2 | RP101C-ND | cable tie | Digi-Key  
X3 | VW-4754-500BK | cable | Bi-Tronics  

Table 1: Parts List  

A complete list of parts for constructing one headstage amplifier. †1 National Semiconductor. †2 Linear Technology. †3 KOA. †4 Panasonic. †5 3M (Digi-Key part number). †6 Hirose. †7 Mogami (Bi-Tronics part number).

Construction  

When manufactured, the printed circuit boards are paneled 5-up and routed with breakout points. This not only eases the job of the PCB manufacturer, it also eases handling during soldering.

Construction by hand, rather than by automated mechanism, requires a steady hand, good soldering skill, a fine-tipped soldering iron, and bountiful patience. Mount the lower-profile, passive components first, then follow with the active components, then the taller passive components, the input connector, and lastly the output cable and reference lead. When soldering each component, it helps to tin a minute amount of solder to one pad before placing the component and applying heat at that pad to fix the component’s position. After that, the remaining leads can be soldered with relative ease. Various stages of assembly are depicted photographically below.

After all wiring is completed, the board is protected with a series of layers. The first is a single layer of black electrical tape for insulation, followed by a layer of carefully overlapped foil tape which is brought in contact with the cable’s overall shield. Finally, a layer of heat shrink tube is applied to protect the foil and provide strain relief for the cable-to-board solder joints.

Operation  

Operation is straightforward. The headstage is first connected to the secondary amplifier to provide a source of power, and then attached to the electrode and a ground reference. No adjustments are necessary or even possible. During normal operation, the headstage gets slightly warm to the touch.
Results

These headstages have been in use in our laboratory at Caltech for more than a year and have supported hundreds of recordings. They work well, are reliable, and produce excellent neural data. Data were collected for analysis below using the headstage in conjunction with a mating secondary amplifier which provides additional gain, and additional filtering.

A sample neural recording is presented in figure 4. This recording was selected for good isolation of a number of cells, but is by no means unusual or exceptional. For additional example data, please see related publications (e.g., Pezaris, 2000).

Plots of noise versus frequency for various input loadings can be seen in figure 5. Resistors
Figure 4: Sample Recording
An example recording made with the headstage in conjunction with the matching secondary amplifier of neural signals from a tetrode. Notice the action potentials (spikes) of varying heights across the four channels; each set of distinct heights is from a different cell. (cmem4714s.au)

of 1 kΩ through 10 MΩ by decades were used in lieu of electrodes between the amplifier inputs and ground, adding the load resistance in parallel to the designed input filter at the first stage of amplification. The family of graphs depicts the noise spectrum for the range input loads: the set of curves all start with a common feature, namely a maximum at about 0.7 Hz, and depart from there with increasing frequency depending upon the input load. Data were recorded in a Faraday cage, with additional steps taken to minimize external interference, at a sampling rate of 25 kHz for 1000 s. Signals passed through a 10 kHz anti-alias filter before conversion, generating both the ripples at frequencies above 1 kHz, and the sharp cutoff at 10 kHz evident in the graph. Although not depicted for reasons of clarity, recordings were also made with input loads of 0 Ω (shorted inputs), and the spectra were indistinguishable from those with 1 kΩ loads.

A plot of gain over frequency can be seen in figure 6. To generate this figure, a noise source of known amplitude was fed to the input of the headstage through a 1 MΩ resistor, and both the input and output were captured. The spectrum of the output was then normalized by the spectrum of the input, generating an estimate of the transfer function over frequency for the amplifier. The low-frequency cutoff is compounded by later stages of amplification in the instrumentation equipment, and the ripples above 1 kHz are due to mismatching of the anti-alias filter responses. Effects from 60 Hz interference have been removed digitally with a non-linear filter.

The measured power consumption was NNN±MMM mW for the total of six units which have been built.
Figure 5: Noise Response
*Input-referred noise versus frequency for input loads of 1k, 10k, 100k, 1M, 10M.*

Figure 6: Gain Response
*Gain versus frequency measured with white noise input of 0.1 mV RMS and an input loading of 1 MΩ.*
Improvements

Future versions of the headstage will use an inverting configuration for the second stage to improve high-frequency rejection, and provide an overall negative system gain when used with secondary amplifiers. The negative system gain is desirable to bring extracellular action potentials into the positive realm for ease of visualization.

Summary and Conclusions

A low-noise four-channel headstage amplifier for making neuroelectrical recordings has been presented. Technical specifications, measured performance, parts list, and sources have been supplied, allowing the reader to readily duplicate the design. For additional information, including construction advice, Gerber plots and the like, please contact the author. Commercial concerns please note that this design is part of a patent-pending system, and the author should be contacted regarding any for-profit uses.

Sources

Advanced Circuits
21100 E 33rd Drive
Aurora, CO 80011
800.289.1724
http://www.4pcb.com

Digi-Key
701 Brooks Avenue South
Thief River Falls, MN 56701-0677
800.344.4539
http://www.digikey.com

Thorlabs
435 Route 206
Newton, NJ 07860
973.597.7227
http://www.thorlabs.com

Surface Mount Distribution
16321 Gothard Street, Unit G
Huntington Beach, CA 92647
714.841.4556

Bi-Tronics
10 Skyline Drive
Hawthorne, NY 10532
800.666.0996
http://www.bitronics.com

National Semiconductor
http://www.national.com

Linear Technology
http://www.linear.com

One, two, into the amplifier, the electrified two, into the amplifier, and you got to get to, into the amplifier, one-two into the amplifier.
— SOUL COUGHING (Rolling, El Oso, 1998)