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New designed EEG amplifier – theoretical calculations and experimental recordings

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A very low noise amplifier, capable of recording signals in the nV range, over a very large frequency band (0.1 Hz – 0.4 MHz) was designed and built. The amplifier was conceived as a tool that will be used to record EEG signals and evoked potentials. The electronic design of the amplifier is based on differential cascodes (JFET - BJT transistors connected in a common source - common base configuration). The equivalent input noise of the amplifier is $7\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ measured at 22 Hz, corresponding to $1/f$ corner frequency. The amplifier's signal-to-noise ratio is 125 dB. An EEG signal, was recorded using the amplifier then filtered and compared to some EEG signals taken from the scientific literature.

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1. Introduction

The EEG signal containing significant biological information span over a large frequency range. Even if the usual EEG medical examination takes into consideration only the lower part of the signal spectrum (usually up to 40 Hz), the whole measured frequency spectrum is analysed in this work. A higher frequency component, present in an EEG signal, has a lower amplitude than a lower frequency component present in the same signal. Therefore the signal can be measured only within the limits of the equipment used. If a certain frequency component has a lower amplitude than the equivalent input noise, measured at that specific frequency, it cannot be distinguished from the noise. Our amplifier is designed to record signals in the nanovolt amplitude range, over a large frequency range.

2. A short description of the amplifier prototype

The described device is an instrumentation amplifier with differential inputs (Fig. 1). SMA connectors are used on both inputs, while the output uses a BNC connector. Each input signal passes through a pair of JFET-BJT cascode, which is the first gain stage of the amplifier. The use of two in parallel cascodes, for each input, greatly decreases the noise level [1], under a high input resistance. High-end LT1028A operational amplifiers are used for the second gain stage and the negative feedback loops.

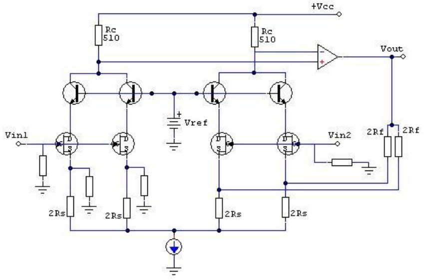

Fig. 1. The simplified schema of the amplifier.

The main characteristics of the amplifier (measured in the laboratory) are shown below.

Overall characteristics [2]:
Differential voltage gain: 36 dB
Gain bandwidth: 0.1 Hz – 0.4 MHz
Common mode rejection ratio: 95 dB
Differential input resistance: 20 MΩ
Output resistance: 50 Ω
Equivalent input noise voltage: $7\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$
(for frequencies higher than 22 Hz).

3. Equivalent input noise calculations for the first gain stage

The equivalent signal circuit, based on the circuit schema of the amplifier, is shown in Fig. 2.

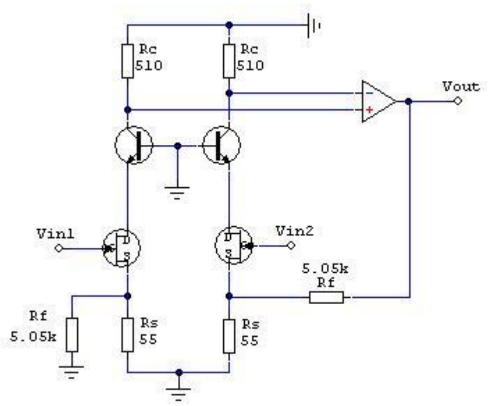

Fig. 2. Equivalent signal circuit.

For the noise calculations, the transistors (Fig. 2) were modeled as in Fig. 3. Calculations are made only for one channel. The second channel has the same component values, so the noise values are identical to those calculated for channel 1.

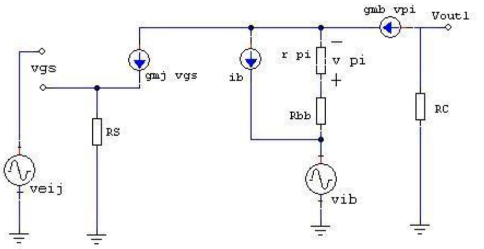

Fig. 3. Transistor model for noise calculations.

In Fig. 3, after applying Kirchhoff's laws, one obtains:

$$v_{eij} + v_{gs} + v_S = 0$$

$$v_S = R_S g_{mj} v_{gs}$$

$$i_b = g_{mj} v_{gs} - g_{mb} v_\pi$$

$$v_{out1} = -g_{mb} \cdot v_\pi \cdot R_C$$

where v_{eij} is the equivalent input noise of the JFET transistor, g_{mj} and g_{mb} are the transconductance for the JFET, respectively BJT, i_b is the equivalent current noise of the BJT.

Therefore, the output noise voltage can be written as:

$$v_{out1} = -R_C \left(v_{eij} \cdot \frac{1}{\frac{1}{g_{mj}} + R_S} - i_b \right)$$

The JFET's trans conductance is: $g_{mj} = \frac{2I_D}{V_{GS} - V_p}$.

From the 2SK170 JFET datasheet, it results that the pinch-off voltage, $V_p = -0.6\ \mathrm{V}$ [6] and the drain current is $I_D = 0.008\ \mathrm{A}$. Because $V_{GS} << V_p$, the gate-source voltage, V_{GS}, will be approximated to zero. Therefore the numeric value of g_{mj} is: $g_{mj} = 0.026\ \mathrm{A/V}$.

For the equivalent input voltage noise of the JFET transistor, the following formula is used [3]:

$$\frac{\overline{v_{eij}^{\ 2}}}{\Delta f} = 4kT \cdot \frac{2}{3} \frac{1}{g_{mj}} + K_f \frac{I_D}{g_{mj}^{\ 2} \cdot f}$$

where K_f is a constant depending on the FET used, f is the frequency at which v_{eij} is calculated.

From the 2SK170 JFET's datasheet it results that $K_f = 81.8\ \mathrm{mA}$.

Therefore, for a given frequency, $f = 22\ \mathrm{Hz}$, the equivalent input noise is: $\frac{v_{eij}}{\sqrt{\Delta f}} = 6.22\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$.

Using two cascade in parallel for each channel with the independent noise sources, the equivalent noise of an input channel is obtained dividing by $\sqrt{2}$ the noise values of one cascade, resulting:

$$\frac{v_{eij}}{\sqrt{\Delta f}} = 4.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

For the equivalent input current noise of the BJT transistor, the following formula is used [2]:

$$\frac{\overline{i_b^{\ 2}}}{\Delta f} = 2 \cdot q \cdot \left(I_B + K_{fbjt} \cdot \frac{I_B}{f} \right)$$

where K_{fbjt} is a constant depending on the BJT used. Ignoring the $1/f$ component $(K_{fbjt} = 0)$, the equivalent input noise value becomes:

$$\frac{i_b}{\sqrt{\Delta f}} = 25\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$$

Because v_{eij} and i_b are uncorrelated noise sources, the output noise voltage of the amplifier is of the form:

$$v_{out1} = -R_C \left(\sqrt{\left(v_{eij} \cdot \frac{1}{\frac{1}{g_{mj}} + R_S} \right)^2 + i_b^{\ 2}} \right)$$

For a given frequency, $f = 22\ \mathrm{Hz}$, it results:

$$\frac{v_{out1}}{\sqrt{\Delta f}} = 24.68\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

The value of the equivalent input noise of one channel of the amplifier is given by the formula:

$$\frac{v_{in}}{\sqrt{\Delta f}} = \frac{\frac{v_{out1}}{\sqrt{\Delta f}}}{A} = \frac{24.68 \frac{nV}{\sqrt{Hz}}}{9.1} = 2.71 \frac{nV}{\sqrt{Hz}},$$

at a given frequency, $f = 22\ \mathrm{Hz}$.

To obtain the total input noise of the amplifier, we need to add the noises coming from each channel. The two channels are identical and independent of each other. Therefore the total input noise of the amplifier has the following formula:

$$v_{in\ \mathrm{total}} = \sqrt{v_{in1}^{\ 2} + v_{in2}^{\ 2}} = \sqrt{2 \cdot v_{in}^{\ 2}} = v_{in} \cdot \sqrt{2}$$

For a given frequency, $f = 22\ \mathrm{Hz}$, it results the following noise spectral density:

$$\frac{v_{in\,total}}{\sqrt{\Delta f}} = 3.83\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

4. Calculation of the voltage gain

For the first gain stage, the voltage gain is (Fig. 4):

$$A_1 = \frac{v_{out1}}{v_{in}}.$$

Considering that no noises are present in Fig. 3, we apply a signal (v_{in}) at the gain stage input. We obtain the following relation:

$$v_{out1} = -R_C\left(v_{in}\cdot\frac{1}{\frac{1}{g_{mj}}+R_S}\right) = -\frac{g_{mj}R_C}{1+g_{mj}R_S}\cdot v_{in}$$

Because $g_{mj}R_s \approx 962 >> 1$, the voltage gain becomes:

$$A_1 = \frac{v_{out1}}{v_{in}} \approx -\frac{R_C}{R_S} = -9.1$$

The total voltage gain of the amplifier is [7]:

$$A_{\text{total}} = 1+\frac{R_F}{R_S} = 91.8$$

The second gain stage is made of a LT1028A operational amplifier which has a voltage gain, $A_2 = \frac{A_{\text{total}}}{A_1} = 10\cdot$

5. Signal to noise ratio

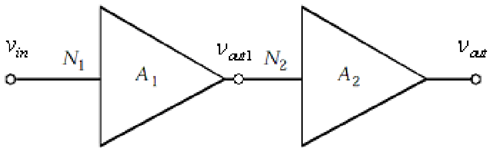

Fig. 4. Amplifier's gain stages.

The signal to noise ratio (SNR) of two gain stages (Fig. 4) is calculated using [6]:

$$SNR = \left(\frac{S}{N_1}\right)^2\cdot\frac{1}{1+\left(\frac{N_2}{A_1N_1}\right)^2} \approx \left(\frac{S}{N_1}\right)^2$$

For an output signal with an amplitude of $S = 10\,\text{mV}$, at given frequency, $f = 22\,\text{Hz}$, it results: $SNR = 1.83\cdot10^6$ ($SNR_{dB} = 125$ dB).

6. Noise measurements

The amplifier internal noise has been measured using a Stanford Research SR530 Lock-in Amplifier. The 1/*f* corner frequency is corresponding to 22 Hz. The equivalent input noise voltage is $7\,\text{nV}/\sqrt{\text{Hz}}$, at frequencies higher than 22 Hz [2], while at a given frequency, $f = 10\,\text{Hz}$, the equivalent input noise voltage is $11\,\text{nV}/\sqrt{\text{Hz}}$ (Fig. 5).

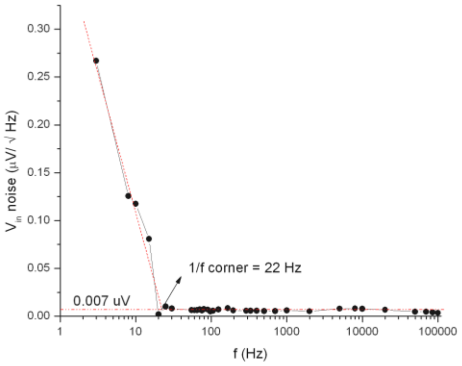

Fig. 5. Equivalent input noise voltage of the amplifier versus frequency.

The equivalent input noise difference between the theoretical value and the experimental one can be explained by the following factors: approximations used in modeling the transistors, the resistance noise which was not taken into account in this calculation, component matching and wiring/soldering of the electronic components.

7. EEG measurements

The EEG signals were recorded using: the described amplifier, the oscilloscope LeCroy Wave Jet 332, non-polarisable Ag/AgCl electrodes, all components being placed into a Faraday cage.

The electrodes were placed in the Fp1 and Fp2 locations, according to the "10-20" electrode placement standard. The recorded signal has a frequency range of (0 – 5) kHz. The bulk signal, as it appeared on the oscilloscope display, is presented in Fig. 6.

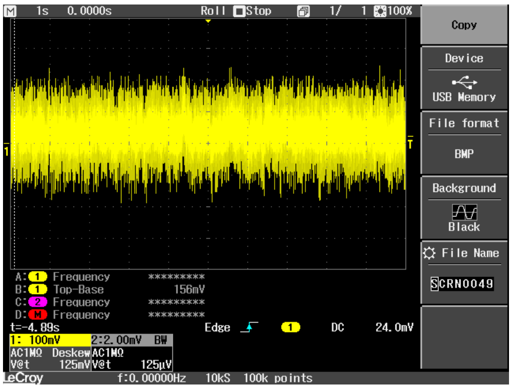

Fig. 6. EEG signal on the oscilloscope display.

Fig. 7 shows the consequence of applying a 45 Hz low-pass filter to the recorded signal. This resulted wave form is what it is usually recorded in hospitals, during a regular EEG recording.

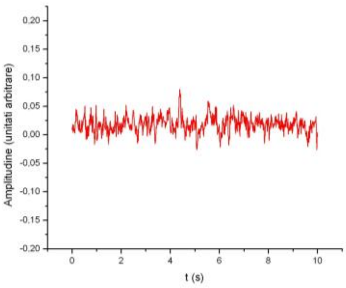

Fig. 7. EEG signal after applying a 45 Hz low-pass filter.

For comparison reasons, Fig. 8 shows a 10 s interval of raw data from a single channel recording, as it was found in ref. [4]. The resemblance with the signal featured in Fig. 7 is obvious.

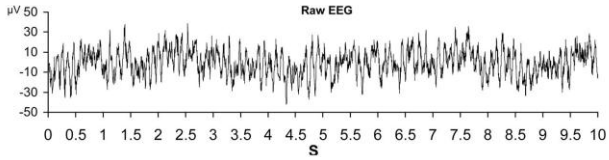

Fig. 8. EEG signal - 10 s interval of raw data from a single channel [3].

The same raw EEG signal from Fig. 6 was filtered with a band-pass filtered in the (8-13) Hz frequency range, in order to see the alpha rhythm. Fig. 9 is a detail of the resulted filtered signal. Only a data interval of 4 s is displayed, in order to have a better view of the alpha rhythm.

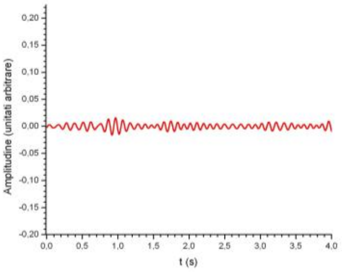

Fig. 9. EEG signal after applying a 8-13 Hz band-pass filter.

After filtering the raw EEG signal with a band pass-filter in the (8-13) Hz frequency range, the beta rhythm was obtained (Fig. 10).

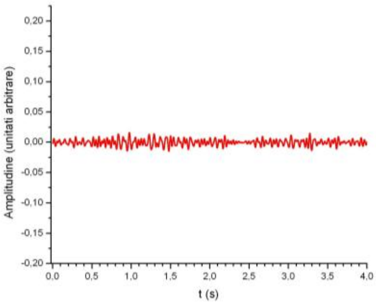

Fig. 10. EEG signal after applying a (13-30) Hz band-pass filter.

It is important to emphasize that the recorded and filtered signals, presented in the Figs. 8 and 9, are similar to the rhythms previously reported in the ref. (Fig. 11 [4]).

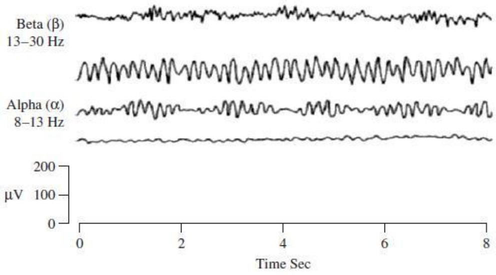

Fig. 11. EEG rhythms reported in the ref. [4].

8. Conclusion

The theoretical noise calculations are close to the real noise measurements. The smallest signal that can be recorded using the described amplifier (outside the $1/f$ zone) has voltages as low as $7\ \text{nV}/\sqrt{\text{Hz}}$. This is a useful requirement when trying to record small amplitude evoked potentials. Also, one can notice that the higher the frequency, the lower the amplitude of the signal. The amplifier frequency range, 0.1 Hz - 385 kHz, and the high amplifier sensitivity, combined with the low input noise, are the key features of this amplifier. The SNR of the amplifier is 125 dB.

From a raw EEG signals, containing frequencies up to 5 kHz, alpha and beta rhythms were extracted.

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