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A CMOS Instrumentation Amplifier for EEG front end system

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***Abstract*—This paper subjects to an application of instrumentation amplifier, which is a low frequency device EEG (electroencephalogram). As EEG signals are exhibiting the frequency range of 1Hz to 200Hz, we have designed a bandpass filter within an instrumentation amplifier itself, using 180 nm technology. It consists of the same band of low frequency with high CMRR of 77 dB, low input referred noise of 1.977 micro-volt per Hz, and with a good linearity input referred IIP3 of 29 dBm. The IA covers the minimum area of 0.006600 mm-square.**

***Index Terms*—EEG (electroencephalogram), IIP3 (Input intercept point), IA (instrumentation amplifier), linearity.**

I. Introduction

An **instrumentation amplifier** is a type of differential amplifier that has been outfitted with input buffer amplifiers, which eliminate the need for input impedance matching and thus make the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedances. Instrumentation amplifiers are used where great accuracy and stability of the circuit both short and long-term are required.

Electroencephalography (**EEG**) is an electrophysiological monitoring method to record electrical activity of the brain. It is typically non-invasive, with the electrodes placed along the scalp, although invasive electrodes are sometimes used in specific applications. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain. In clinical contexts, EEG refers to the recording of the brain's spontaneous electrical activity over a period of time, as recorded from multiple electrodes placed on the scalp [18].

In this paper a CMOS instrumentation amplifier of an analog front-end section of an EEG system is presented. Besides the band-pass filter, the important points are high common mode rejection ratio (CMRR), very low noise, high linearity and minimum area of designing.

This amplifier includes the following blocks as shown in fig. 1 two transconductance stages, current mirrors, high pass filter low pass filter, and differential amplifier stages.

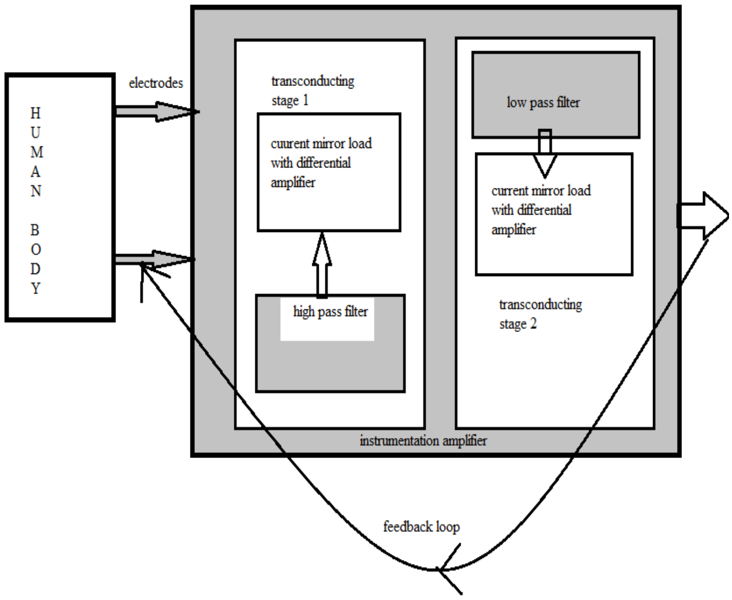

Fig. 1 Block diagram of proposed instrumentation amplifier.

Each of the electrode is connected to one input of a differential amplifier (differential inputs); a common system reference electrode is connected to the other input of each differential amplifier. This instrumentation amplifier will now amplify and boost up the weak signals coming from electrodes. Voltage gain observed during simulation is up to 60 to 80 dB. A typical adult human EEG signal ranges about 10 µV to 100 µV in amplitude when it is measured and observed through scalp and is about 10–20 mV when measured from subdural electrodes.

To detect such a small range input signals in the presence of high flicker noise there is a need of an instrumentation amplifier with high CMRR and low noise. This paper has a total of five sections. Section I concludes with the introduction of EEG and instrumentation amplifier, section II accounts for the related works in this area so far, section III shows the complete schematic of instrumentation amplifier used and the working frequency waves (which has to be passed), section IV is about all simulation and observed results of the IA and finally section V with a brief conclusion.

II. Related Works & Background

Andreas *et al.* [17] developed an instrumentation amplifier with CMRR intended for imaging of cancer biomarkers. Local current feedback IA topology, each local

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loop contains a smaller number of internal parasitic poles and thus, this topology potentially offers a higher operating BW for a given current consumption. One advantage of the current mirror load over the resistor load implementation is insensitivity to the input offset voltage of the sensing (or loop) amplifier connected across the input and output nodes of the current mirror load.

R.Martin *et al*. [7] presents an instrumentation amplifier for EEG acquisition system which draws 500 µA current only. This system consists of the MUX, programmable gain amplifier, a calibration oscillator and an instrumentation amplifier. This full custom design gives the solution for flicker noise problem.

Witte *et al*. [4] provides the two different current feedback approaches. One is indirect current feedback instrumentation amplifier in which the input common mode voltage signal and reference common mode signal are independent of each other. This comes at the cost of an increased current dissipation. Therefore, the direct current feedback instrumentation amplifier is used where both common mode voltages are dependent, & low power dissipation is required. Indirect current feedback is used where linearity and accuracy is required.

III. METHODOLOGY

Brain neurons contains various bands, which are present at the low frequency, they are categorized and given below:

Delta is the frequency range up to 4 Hz. It tends to be the highest in amplitude and the slowest waves. It is seen normally in adults in slow wave sleep. It is also seen normally in babies.

Theta is the frequency range from 4 Hz to 7 Hz. Theta is seen normally in young children. It may be seen in drowsiness or arousal in older children and adults; it can also be seen in meditation. Excess theta for age represents abnormal activity.

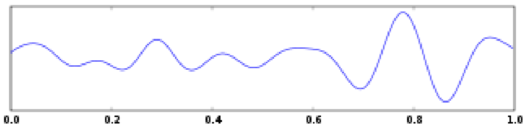

Fig. (a) Theta waves[18]

Alpha is the frequency range from 7 Hz to 14 Hz. Hans Berger named the first rhythmic EEG activity he saw as the "alpha wave". This was the "posterior basic rhythm" (also called the "posterior dominant rhythm" or the "posterior alpha rhythm"), seen in the posterior regions of the head on both sides, higher in amplitude on the dominant side. It emerges with closing of the eyes and with relaxation, and attenuates with eye opening or mental exertion.

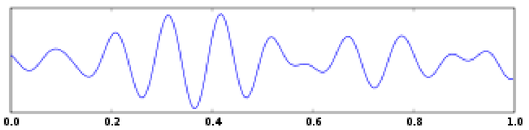

Fig. (b) Alpha waves[18]

Beta is the frequency range from 15 Hz to about 30 Hz. It is seen usually on both sides in symmetrical distribution and is most evident frontally. Beta activity is closely linked to motor behavior and is generally attenuated during active movements. Low amplitude beta with multiple and varying frequencies is often associated with active, busy or anxious thinking and active concentration.

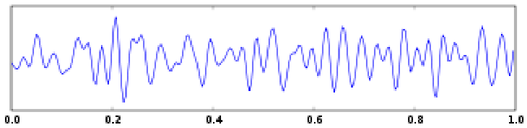

Fig. (c) Beta waves[18]

Gamma is the frequency range approximately 30–100 Hz. Gamma rhythms are thought to represent binding of different populations of neurons together into a network for the purpose of carrying out a certain cognitive or motor function.

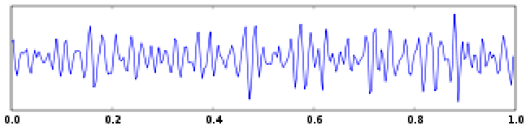

Fig. (d) Gamma waves[18]

Mu ranges 8–13 Hz, and partly overlaps with other frequencies. It reflects the synchronous firing of motor neurons in rest state. Mu suppression is thought to reflect motor mirror neuron systems, because when an action is observed, the pattern extinguishes, possibly because of the normal neuronal system and the mirror neuron system "go out of sync", and interfere with each other.

Fig 2. Shows the schematic diagram of proposed Instrumentation amplifier, with inbuilt band-pass filter. It consists of the few processing blocks such as input stage, low-pass filter, transconductance stage (GM), high pass filter, current mirror load and output stage.

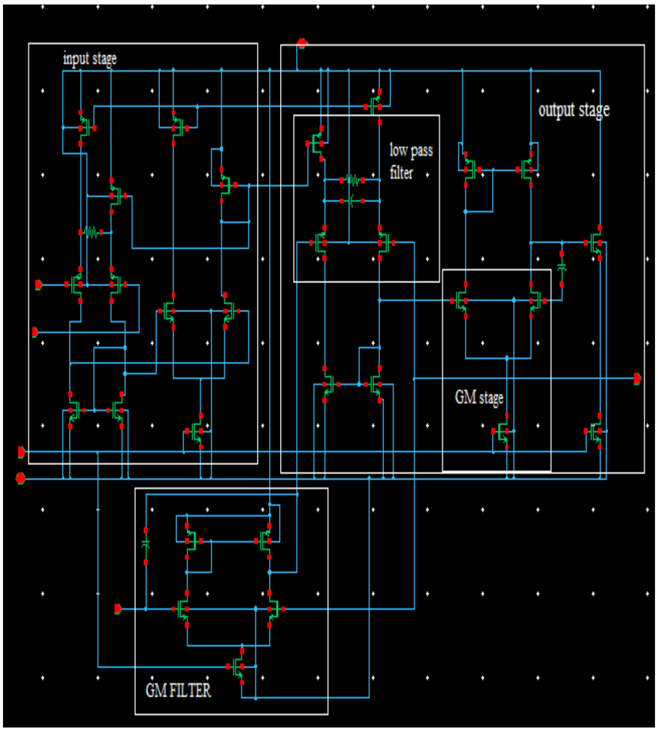

Fig. 2 schematic diagram of proposed IA

The GM stage uses a current mirror load and source network, differential amplifiers outputs serves exactly to maintain and balance the drain currents of input and output stages. Since the opposite face input transistors are identical and same current is drawn across their drain terminal, the input voltage drop across R1. At the output transconductance stage, same drain currents are drawn at the differential pairs of output terminal. As a result output voltage V0 appears at the output resistance R2 (shown in low-pass block). Placing a capacitor C1 across R2 will create a dominant pole, which sets the higher 3dB frequency of the IA (C1 and R1 acts as a low-pass circuit).

The purpose of designing the band-pass filter is to reduce the unwanted spectrum in the form of noise. With this band of 0.3 Hz to 250 Hz only desired signal would be allow to pass and rest of the spectrum is removed. The low-pass filter, a capacitor C1 and a resistor R1 is connected in parallel, which causes a pole at :

$$F_h = 1/ (2*\pi*R1*C1)$$

The high-pass filter is more difficult to obtain from the passive R and C action simultaneously for such a low frequency of 1 Hz. So a another feedback loop around the output circuit is implemented. Fig. 2 shows the GM filter which acts as a resistor, but it offers advantages over a real resistor. As it is possible to make its transconductance low, a high identical equivalent resistor can be obtained. Also there is no resistive loading of the output of the output. Hence a zero is obtained at frequency (lower 3dB cut-off frequency):

$$F_l = GM/ (2*\pi*C_{filter})$$

To improve the CMRR and low input referred noise the input transistors were made to work in moderate inversion mode. For a proper matching of devices both W and L , width and length of the input transistor are larger than minimum feature size.

The load transistors at the bottom of input stage are designed according to its transconductance, which should be three times more than that of input transistors.

Current feedback IA there are few number of internal parasitic poles and thus this circuit offers a higher 3dB frequency and operating bandwidth. While in case of other feedback such as direct and indirect feedback [4] there are more number of poles associated with each stage and hence operating bandwidth reduces.

Circuit is designed in virtuoso design environment, using 180nm technology. Library files included is UMC18CMOS technology files, all the components are placed from the same library files. Three terminal resistors and capacitors are used and 3rd terminal is connected to VDD as body is of P-type. Total of 29 MOS with 2 resistors and 3 capacitors are required with a power supply of 1.8V. Further for calculations of IIP3 and intermodulation terms separate ports are applied. Harmonic balance analysis is done using two ports at input and output terminal respectively .

Fig 3 shows the band-pass output response of the proposed IA. Here we have to take 60 dB gain in account, rather than 80 dB. The reason behind this is the stability, which is much more in case of 60 dB gain as compared to 80 dB. As gain increases stability decreases. Hence trade-off between gain and stability is kept in mind, while designing this EEG based Instrumentation amplifier.

IV. SIMULATIONS AND RESULTS

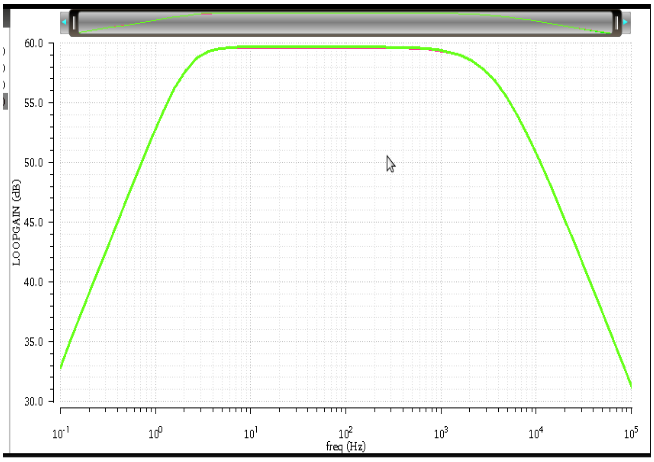

Fig. 3 gain v/s frequency curve.

This region the IA is stable i.e from 0.3 to 250 Hz which is good enough for detecting the small signals. The above graph clearly shows for lower values of R1, the gain is 60 dB but we have to trade off between gain and stability here. Thus we cannot reduce R1 below 100 ohm (R1 is the input stage resistance as shown in fig. 2) The above gain will boost up the small micro volts signals from the electrodes and will allow the device to compare the signals with actual EEG waves.

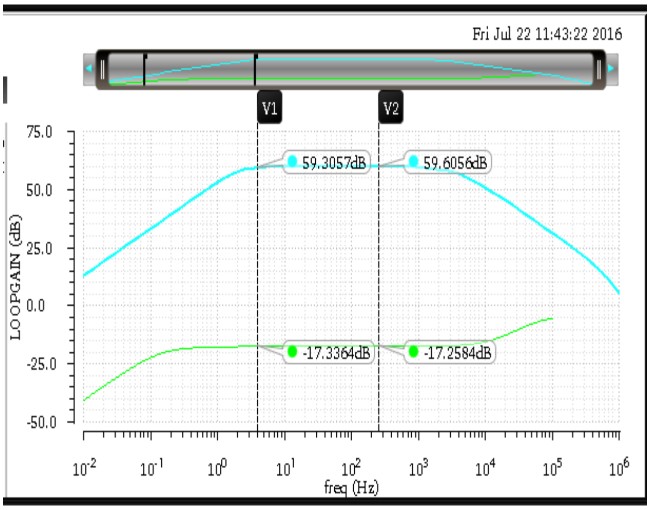

Fig.4 CMRR calculation of proposed IA.

$$CMRR = (Ad / Ac)$$

Where Ad is differential gain and Ac is common –mode gain.

The **common-mode rejection ratio** (CMRR) of a differential amplifier (or other device) measures the ability of the device to reject common-mode signals, those that appear simultaneously and in-phase on both amplifier inputs. An ideal differential amplifier would have infinite CMRR; this is not achievable in practice. Calculating CMRR from fig 4 we get, CMRR at 3dB cut-off frequency = 60-[-17]. Hence CMRR = 77 dB which is good at this frequency (which is one

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of the target result).

Moving towards the stability criterion, both phase and gain margin is positive for this gain of 60 dB, which is also an important factor in designing of circuits.

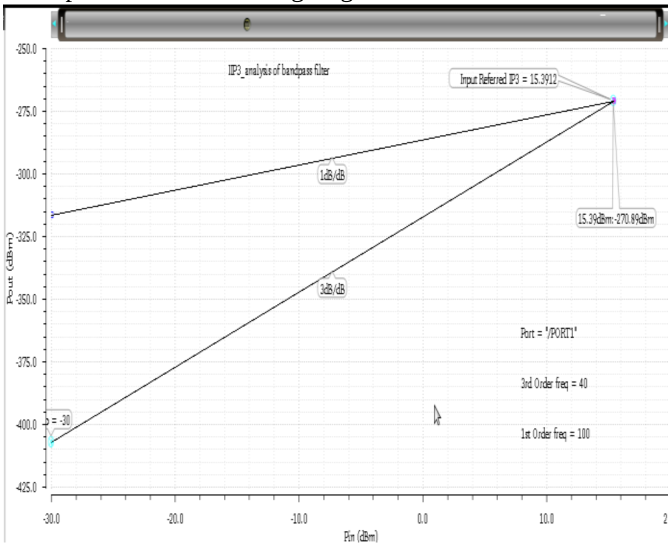

Fig. 5 IIP3 analyses of bandpass filter in IA.

The intercept point is obtained graphically by plotting the output power versus the input power both on logarithmic scales (e.g., decibels) shown in fig 5. Two curves are drawn; one for the linearly amplified signal at an input tone frequency, one for a nonlinear product. Both curves are extended with straight lines of slope 1 and n (3 for a third-order intercept point). The point where the curves intersect is the intercept point. It can be read off from the input or output power axis, leading to input or output intercept point, respectively (IIP3/OIP3). When comparing systems or devices for linearity, then, a higher intercept point is better. This device with an **input-referred third-order intercept point** of 15.39 dBm is driven with a test signal of −30 dBm. This power is 45.39 dB below the intercept point; therefore nonlinear products will appear at approximately 2x45.39 dB below the test signal power at the device output (in other words, 3×45.39 dB below the output-referred third-order intercept point).

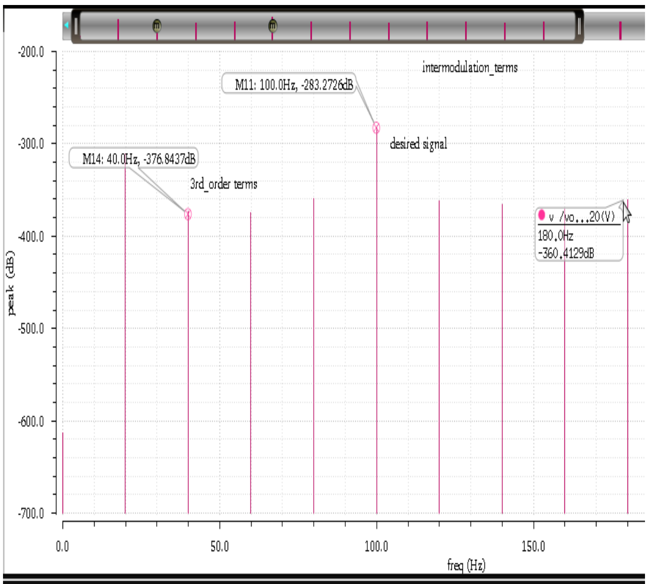

Fig.6 intermodulation terms of the simulated filter.

Intermodulation arises when more than one tone is present at the input. A common method for analyzing this distortion is the "two-tone" test. We assume that two strong interferers occur at the input of the receiver, specified by $s(t) = A_1\cos w_1 t + A_2\cos w_2 t$. Here we applied f1 = 100Hz and f2 = 90 Hz. Intermodulation distortion is defined as the ratio of the amplitude of third order harmonics to the amplitude of first order harmonics. So from fig. 6 we are getting the desired signal in the frequency f = 100 + 3*90 and f = 100 – 3* 90. That is f= 370 Hz and 170 Hz. Amplitude next to this frequency is first order intermodulation terms and next to this is second order and so on.

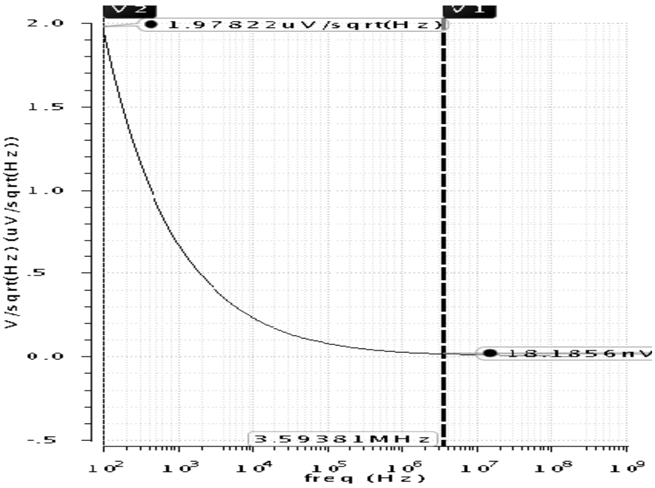

Fig. 7 input referred noise of the filter

There is circuit noise internal to the subcomponents in the front end. This noise will add on to the AWGN, cause interference, and further degrade the SNR. Circuit noise is associated with the electrical components that build the subcomponents, such as resistors and MOS transistors. Fig 7 shows the input referred noise is of 9.77µV which is also low required parameter of the filter.

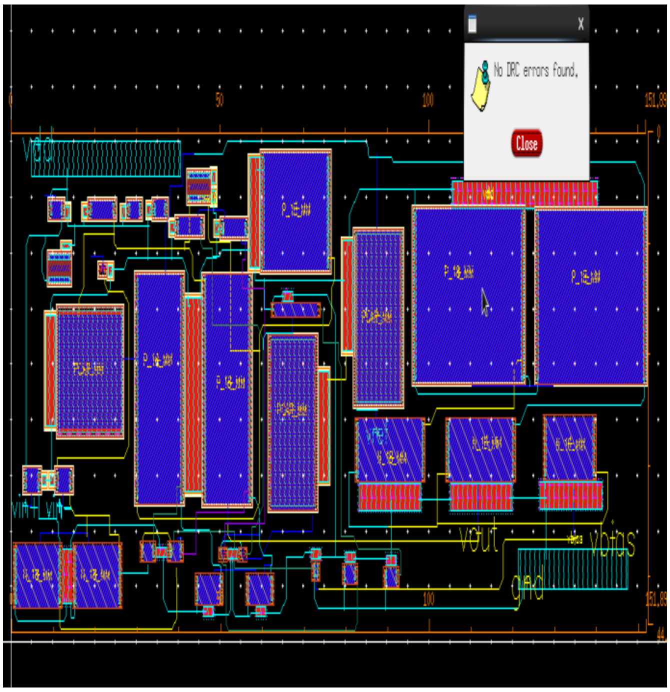

Fig. 8 layout area of the proposed IA

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Volume 5, Issue 7, July 2016

Fig 8 is the **layout** of IA with minimum area with no DRC errors. Resistors are placed apart from power supply in order to achieve low mismatches and minimum resistive layers are used with proper design rules specifications.

Table – 1 summary of the results obtained

S.NO	PARAMETERS	RESULTS OBTAINED
1.	Process technology	180nm technology
2.	CMRR	77 dB
3.	Differential gain	60 dB
4.	Common-mode gain	-17 dB
5.	Slew Rate	38.3V/µS
6.	Area	0.006600mm-sq
7.	Power dissipation	980µw
8.	Bandwidth	0.3-250 Hz
9.	Supply voltage	1.8V
10.	Input referred noise	1.97µV

V. CONCLUSION AND FUTURE SCOPE

This paper provides the instrumentation amplifier for front end EEG system with high stability, linearity, low noise and good CMRR with inbuilt band-pass filter. This circuit plays a major role in getting high gain using transconductance stage.

Use of this type of arrangement is further applied to imaging instrumentation amplifiers [13]-[14] and in many front end section where impedance matching is required.

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