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Research paper

A 76dB 828nV/√Hz Low Noise Bio Signal OTA for Neural Signal Recording Applications

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Abstract

The low frequency, low amplitude biomedical signals which created a tremendous demand amongst clinicians and neuroscience researchers are to be amplified in the range of millihertz to kilohertz by rejecting the dc offsets. This research article presents a Bio Signal OTA (Bio-OTA) with 76dB gain, 828nV/$\sqrt{Hz}$ noise and 390nW power is designed in 90nm CMOS process and also a brief survey on the different types of OTAs used for neuro recording applications is discussed. The Wilson current mirror is used to design 1volt Bio-OTA. The Common mode rejection ratio (CMRR) is obtained as 75dB, power supply rejection ratio (PSRR) is above 88dB and gain bandwidth product (GBW) is 223MHz.

Keywords: *Bio-OTA, Brain Machine Interface, Biopotentials, Neural recording Amplifier, OTA.*

1. Introduction

The robust adaptability of highly sophisticated electronic goods by the present generation laid a path to design and manufacture miniaturized electronics gadgets. This miniature world of electronics spread its wings into many different fields, demanding high processing speed, low power and robust equipments. Microelectronics helped even to enter into low frequency designs apart from high frequency circuit designs. Now electronics in medical field is creating new targets and new challenges; which aim at low voltage portable medical electro-gadgets and implantable biomedical electronics devices to diagnose the critical neural diseases. Low voltage, high speed, low power and low frequency operational amplifiers have shaped as bio-potential amplifiers.

A bio-potential amplifier aims to amplify the very small and weak frequency signals and then filters the signal as per required area of biomedical design. Low power dissipation and high CMRR biomedical designs are targeted for high signal quality and performance. The tremendous progress in amplifier technology made designers to design amplifiers with low noise, high flat gain characteristics and very low power consumption. The electrical neuron signal capturing necessitates the bio-potential amplifier in neural recording applications. The neuron signals are mainly classified as local field potentials (LFP) and neural spikes. These signals are of low amplitudes ranging 1 and 10μVolts with low frequency bandwidth ranging from 0.01Hz to 10 KHz. The signal voltage amplitude and bandwidth of physiological signals in table1 and table2 exhibits the source areas and electrical neuron signals applications.

In this research article a high gain, low noise and very low power consumed Bio-OTA is designed for neuro-electrical applications and a review of different OTAs used in neural recording applications is also presented. The organization of article is as follows: Section II depicts the survey of different OTAs used in neuro-electrical applications. Section III presents the systematic design approach of high gain, low noise and low power Bio-OTA. Section IV showcases the simulation results of the proposed Bio-OTA. Section V concludes this article summarizing the results of the Bio-OTA for neural recording systems.

Table 1. Amplitudes and Bandwidths of neuro-electrical signals [36].

Nerve Signal	Amplitude	Bandwidth
EEG	1 to 10mV	1mHz - 200Hz
LFP	0.5 to 5mV	1mHz - 200Hz
EAPs	50 to 500μV	100Hz -10KHz
IAPs	10 to70mV	100Hz -10KHz
Ionic Currents	1 to 10nA	1mHz -10KHz
Redox Currents	100f to10μA	1mHz -100Hz

Table2. Source Areas and Applications of neuro-electrical signals [36].

Bioelectrical Signal	Source Area	Applications (Recording)
EEG	Brain	Encephalography/Scalp
ECG	Heart	Cardiac
ECoG	Brain	Cerebral Cortex
EOG	Eye Dipole	Eye Movement
EMG	Muscle	Muscle Activity

2. Operational Transconductance Amplifier (OTA) used in Neural Recording Applications: A Review

OTA is an amplifier where differential input voltage controls an output current. Therefore, it is referred as voltage controlled current source (VCCS), whereas op-amp is a current controlled current source (CCCS). An additional input biasing current terminal is required to control transconductance of an operational amplifier. The class A amplifier is usually referred as conventional OTA, generates maximum output currents that is equal to the applied bias current. CMRR, gain, PSRR, unity gain bandwidth (UGW), phase margin, offsets and slew rates are the main characteristics of an OTA. It has wide applications in voltage-controlled amplifier, filters and ADCs. A lot of research is done and still carried on, in the field of OTA with high UGW, high gain and low power consumptions. Many different OTA configurations are proposed and discussed in the literature; few of commonly used are reported in this paper.

Single stage OTA is a very high speed, high UGW and least complex configuration [2]. Here pull up transistors forms the current mirror and input transistors makes the differential pair, so it is termed as differential amplifier. The output impedance is relatively very low, which degrades the magnification.

Two Stage OTA is obtained by adding another stage to the single stage OTA. It overcomes the limitation of low gain nature of the single stage. Here one stage provides high gain and other stage produces high output voltage swing. Due to an inclusion of extra stage increases the complexity, hence reduces the speed and increases the power consumption. Extra pull-down voltage biasing transistors are connected to single stage OTA to obtain amplification. DC biasing is provided to the design from inverter shaped connection. The main drawback is; it requires a compensation circuit to stabilize [4].

Telescopic Cascode OTA is a structure with two stacked transistors connected to achieve high output impedances and high gain. Cascoding is a technique to stack transistors on top of another transistor. It reduces the input capacitances to obtain high frequency response by consuming less power, whereas it exhibits limited output swing [3, 23].

Folded Cascode (FC) OTA eliminates the demerits of telescopic OTA. It has better high frequency PSRR. Due to extra current leg devices, input referred noise is increase and operates with high power consumption [7, 24]. The noise efficiency factor (NEF) is improved by using source degeneration resistors.

Gain Boosting OTA further improves gain without adding extra cascode device, thus decreases output voltage swing. It is also known as regulated cascode OTA [9, 22].

There are many other implementations mentioned in literature for improving the performance of the design like current mirror OTA [10], fully differential self-biased OTA [11], current boosting method [12], self Cascoding method [7], current buffer compensation method [13], bulk driven OTA [14], input complementary folded cascode OTA [15], push-pull OTA [8], recycling folded cascode [16], floating gate OTA [21], current division method [20]. Current division and source degeneration comprises of two methods, source degeneration and current splitting. The current division maintains low transconductance by enabling the increase in current levels. Floating gate scheme has inputs with bias, which has attenuation due to input capacitors voltage division. In bulk driven OTA, inputs are operated through bulks of input transistors other than gates [17]. A very low voltage CMOS OTA is designed with rail-rail input/output stages to achieve very high CMRR and PSRR of values about 259.5dB and 123.78dB respectively are the best recorded [18]. In [19], feed-forward techniques are presents to improve speed and to design high frequency operational transconductance amplifying devices. The recycling folded cascode OTA shown in Figure 8 has twice the GBW and slew rate than the conventional folded cascode OTAs in case of single stage amplifiers. No-capacitor feed-forward compensation scheme is used to obtain greater gain and GBW for multi stage amplifiers.

3. Bio-OTA design for Neural Recording Application: A Systematic Design Approach

This research article proposes and presents a Bio-OTA with systematic design approach to amplify the desired low frequency and low amplitude neuro-electrical signals. The designed Bio-OTA is designed and simulated using 90nm CMOS technology for telescopic architecture shown in figure 1. A single stage telescopic OTA is powered by 1V is designed rather than going for more stages because multi staged amplifier is a power hungry. Sizing of transistors is the first and fore most approach to design desired functionality-based Bio-OTA for neural signal capturing applications. The Bio-OTA is a differential input and single ended output telescopic architecture with a cascaded P- channel MOSFETs M_1 and M_2 acts as the input PMOS devices to which the differential input signal voltage sources are connected at gate terminals, M_3 and M_4 acts as the PMOS cascaded stage whereas M_5 and M_6 acts the NMOS load mirrors and Mosfet (M_7) and Mosfet (M_8) are the NMOS cascade stage. Mosfet M_9 and Mosfet M_{10} acts as mirror devices which are biased by 1.08µA current. High gain is achieved due to this reason: The input signal transistor's aspect ratios are increased to obtain high transconductance (g_m) of the transistors which lowers the noise, the lengths of the n-channel MOSFETs M_7 and M_8 are increased and by maintaining the amplitudes and magnitudes of input signal voltages in the range of few nano volts to 60µ volts. The basic criteria for designing the Bio-OTA for good performance are that transistors should operate in saturation.

The saturation drain current equations are given as:

$$I_{Dn} = \frac{(\mu_n \text{ Cox})}{2}\frac{W}{L}[V_{GS} - V_{th}]^2 \tag{1}$$

Equation (1) is the drain current of N- channel MOSFETs.

$$I_{Dp} = \frac{(\mu_p \text{ Cox})}{2}\frac{W}{L}[V_{GS} - V_{th}]^2 \tag{2}$$

Equation (2) is the drain current of P- channel MOSFETs.
The drain currents of pMos and nMos are initially considered as same in (1) and (2). From (1) and (2), transconductance in terms of drain current and $\mathbf{V_{GS}}$ can be defined as

$$g_m = \frac{2 I_D}{V_{GS} - V_{th}} \tag{3}$$

From (3) g_m is defined as the ratio of the output current to input voltage.

$$\text{Therefore} \quad g_m = \frac{I_{out}}{V_{in}} \tag{4}$$

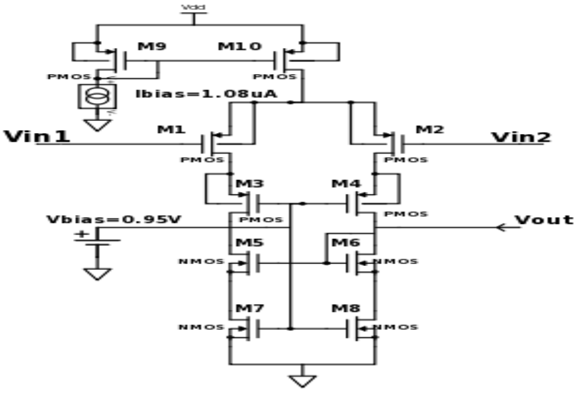

Figure 1: Proposed Bio-OTA

3.1. Small Signal Analysis and Design Approach

The most important parameter in designing a Bio-OTA is open loop gain. The current output (I_{out}) of the Bio-OTA is given by

$$I_{out} = I_{D1} - I_{D2} \tag{5}$$

Where I_{D1} and I_{D2} are the drain currents of M_1 and M_2 respectively.

$$\left.\begin{array}{l} I_{D1} = g_{m1}V_1 \\ I_{D2} = g_{m2}V_2 \end{array}\right\} \qquad (6)$$

Where g_{m1} and g_{m2} are the small signal transconductance of M_1 and M_2 respectively.

Assume $g_{m1} = g_{m2}$ and substitute (6) in (5).

$$I_{out} = g_{m1}\,[V_1\text{-}V_2] \qquad (7)$$

The transconductance can be calculated using design specifications.

$$g_m = \text{GBW}\ C_L \qquad (8)$$

The small signal output resistance is given by

$$R_{out} = R_{O4} \parallel R_{O6} \qquad (9)$$

$$R_{out} = [g_{m4}\, r_{O4}\, r_{O2}] \parallel [g_{m6}\, r_{O6}\, r_{O8}] \qquad (10)$$

Where r_O is the drain-source resistance of transistor.
Now combine (7) and (10) to obtain output voltage.
Therefore

$$V_{out} = I_{out}\, R_{out} \qquad (11)$$

$$V_{out} = g_{m1}\,[V_1\text{-}\ V_2]\,[[g_{m4}\, r_{O4}\, r_{O2}] \parallel [g_{m6}\, r_{O6}\, r_{O2}]] \qquad (12)$$

From above equations we can calculate the open loop gain of Bio-OTA as

$$A_V = \frac{V_{out}}{V_{in}} = g_{m1}\,[[g_{m4}\, r_{O4}\, r_{O2}] \parallel [g_{m6}\, r_{O6}\, r_{O2}]] \qquad (13)$$

Where $V_{in} = [V_1\text{-}V_2]$

Therefore, from (13) we can define open loop gain as

$$A_V = g_m\, R_{out} \qquad (14)$$

The slew rate (SR) as one of the design specifications is defined to quantify the change in voltage for particular time.

$$\text{SR} = \frac{I_{out}}{C_L} \qquad (15)$$

Where C_L is the load capacitance.
Therefore I_{out} is defined from (15) as

$$I_{out} = \text{SR}.\ C_L \qquad (16)$$

The CMRR of the Bio-OTA is obtained by

$$\text{CMRR} = \frac{A_v}{A_c} \qquad (17)$$

Where Av is the differential gain and Ac is the common mode gain.

3.2. Noise Analysis of a Bio-OTA

Only The input referred noise (IRN) is mostly autocraticed due to two main types of noises during neural signal processing. The pink noise or flicker noise at the low frequency signals and other type is shot noise or thermal noise at high frequency signals. The interested area in designing a Bio-OTA is reducing the noise.

The noise current of Mosfet is given by

$$\mathbf{i}_n^2 = 4\ \text{KT}\gamma\ (g_m) \qquad (18)$$

where γ = 2/3.
The thermal noise voltage is defined by

$$S_f = V_n^2 = 4\ \text{KTR}.\ \Delta f \qquad (19)$$

Here 4 KTR is the noise power per unit bandwidth.
For simplicity in design analysis of Bio-OTA assume Δf = 1Hz.

The total IRN voltage (power spectrum density [PSD]) per unit bandwidth is defined by

$$V^2_{in\_n} = \left(\frac{8\text{KT}\gamma}{g_{m1}}\right)\left(1 + \frac{g_{m3,4}}{g_{m1}} + \frac{g_{m5,6}}{g_{m1}} + \frac{g_{m7,8}}{g_{m1}}\right) \qquad (20)$$

The total noise power at the output of Bio-OTA is obtained by

$$P_{n\_OUT} = \frac{KT}{C_L} \qquad (21)$$

Where K = 1.38 X 10^{-23} **Joules** **^{o}Kelvin^{-1}**.

The total Root Mean Square (RMS) noise power at the output of the Bio-OTA is obtained by

$$P_{n\_out\_rms} = \sqrt{\frac{KT}{C_L}} \qquad (22)$$

The total noise power of the Bio-OTA in Watts is obtained by

$$P_{n\_Watts} = \text{KTB} \qquad (23)$$

Where B is the bandwidth.
It is also called as Available power or KTB noise in watts.
The total noise power in small amount is denoted in “dBm”.

Therefore $P_{dBm} = 10\log[\frac{P_{watt}}{0.001}]$ (24)

And $P_{dBm} = 10\log[\frac{KTB}{0.001}]$ (25)

The Noise(N) Efficiency(E) Factor(F) is formulated as

$$\text{NEF} = V_{in\_RMS}\sqrt{\frac{2I_{total}}{\pi U_T\, 4KTB}} \qquad (26)$$

Where $V_{ni,RMS}$ is the IRN (3.16 μV/$\sqrt{Hz}$ @1 Hz), π is 3.14, I_{total} is total flowing current in circuit or biased current (1.08μA), BW is signal bandwidth of physiological signal (10KHz), U_T denotes thermal voltage (25mV), K is the Boltzmann’s constant and T denotes temperature. The NEF obtained is approximately 1.5. The PEF determines the figure of merit (FOM) for efficient power consumption. It is obtained as product of NEF and supply voltage. The PEF obtained is 2.25.

$$\text{PEF} = NEF^2\ V_{DD} \qquad (27)$$

The effective noise temperature of a noise source in the Bio-OTA design is analyzed by

$$T_s = \frac{P_a}{KB}\ \text{degrees in Kelvin} \qquad (28)$$

Where P_a is available noise power.
The effective input noise temperature of a Bio-OTA is defined by using

$$P_{ns} = \text{K}\, T_s\ \text{B Watts} \qquad (29)$$

Where Ts is the effective noise temperature of the source and P_{ns} is the noise power of a noisy source.
Now effective noise temperature of input is given from above equations as

$$T_e = \frac{P_{ne}}{KBG_a} \qquad (30)$$

Where $G_a = \frac{P_{so}}{P_{si}}$ (31)

Here P_{so} and P_{si} are the output signal power and input signal power respectively.

The proposed Bio-OTA is designed by using Wilson current mirror, which achieved a gain of almost 76dB (ie in fact 75.829dB) by shorting the gates of M5 and M6 and the drain of M6 shown in figure 2, consumes the power of 390nW shown in figure 6. The Wilson current mirror is used to have better low cutoff frequency and higher output resistance that results in constant current thus higher gain is obtained. The Bio-OTA achieved input referred noise as almost less than 828nV / √Hz in the gain range of signal bandwidth. The Bio-OTA achieved gain of approximately 76dB from 10mHz to 3.3 KHz. The Phase margin of Bio-OTA is greater than 45^{O}. The simulation results of gain and GBW (223MHz) are shown in figure 2. Figure 3 gives the information about input referred noise of Bio-OTA. Figure 4 and Figure 5 gives information about CMRR and PSRR of the designed Bio-OTA respectively. The Bio-OTA is simulated for gain with load capacitances varying from 0.5fF to 5pF in parametric analysis simulation mode and obtained results are above 75.5dB, shown in figure 7. The designed Bio-OTA is also undergone parametric analysis simulation for gain with respect to (wrt) temperature (temp) effect ranging from 1^{O}C to 50^{O}C shown in figure 8. The figure 9 depicts the parametric noise characteristics wrt temperature. The power characteristics parametric analysis is done wrt temperature and results obtain are in the range of 405nW to 380nW for temperatures from 1^{O} C to 50^{O}C shown in figure 10. The layout of Bio-OTA is designed in 90nm, has a dimension as 190µM X 202µM, shown in figure 11. Different noise analysis is done for Bio-OTA. The total noise power of the Bio-OTA is calculated as $4.14e^{-17}$ watts. The Bio-OTA has good noise power in dBm. The total noise power levels of designed Bio-OTA are very less as the calculated value shows them as -133.82dBm. It also can be represented as133.82pW. The effective noise temperature of noise for Bio-OTA is 300^{O}K and total noise power at the output of Bio-OTA is obtained as 0.828nW. Table 3 depicts the comparative analysis of previous work and proposed Bio-OTA.

4. Simulation Results of Bio-OTA Design

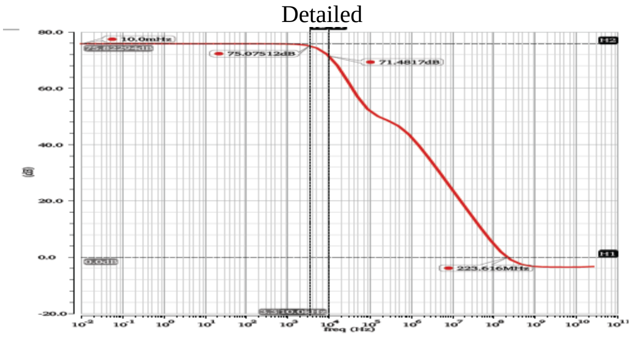

Figure 2: Gain and GBW Characteristics of Bio-OTA.

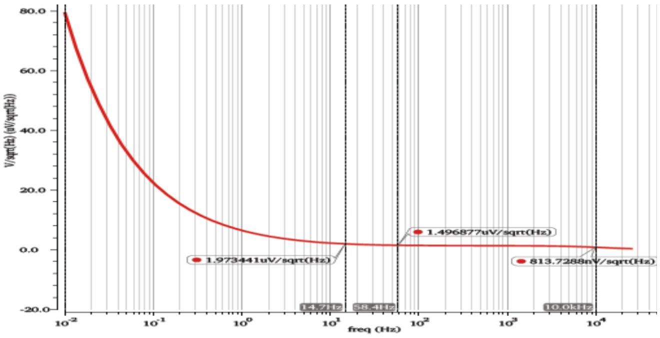

Figure 3: Noise Analysis of Bio-OTA.

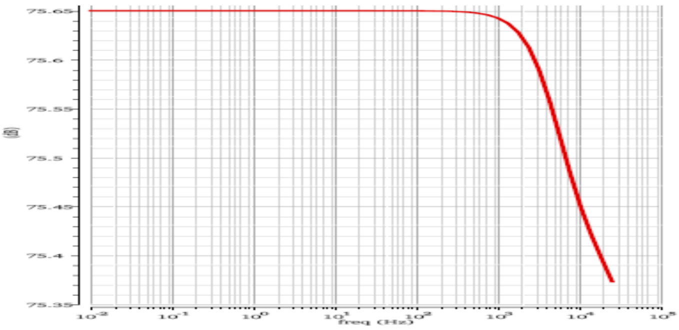

Figure 4: CMRR of Bio-OTA.

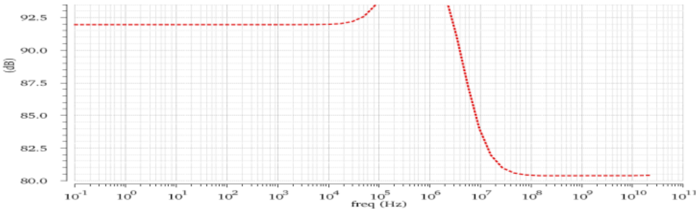

Figure 5: PSRR characteristics of Bio-OTA

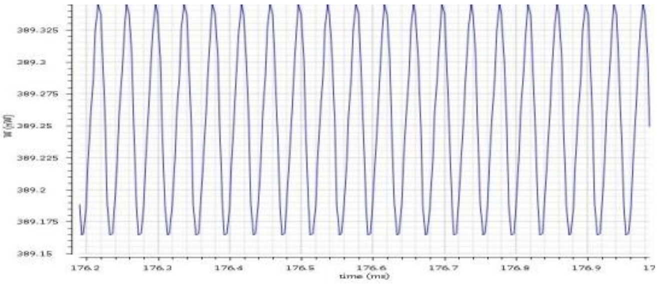

Figure 6: Power Analysis of Bio-OTA.

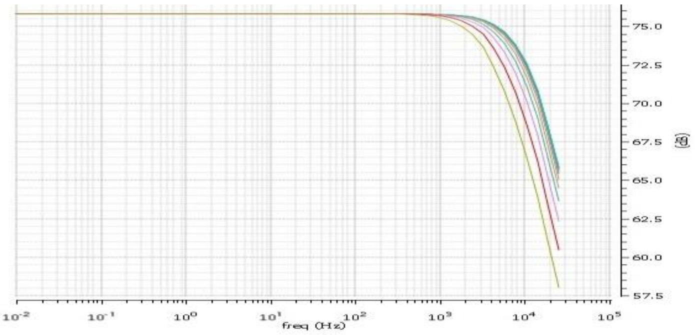

Figure 7: Parametric Gain characteristics wrt C_L

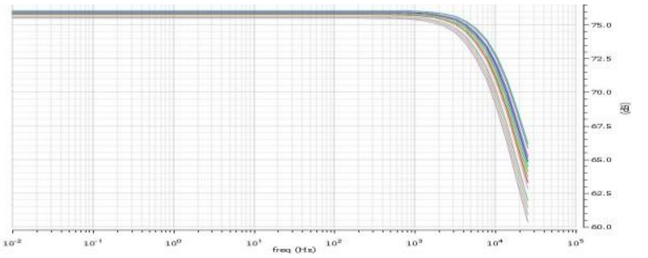

Figure 8: Parametric Gain characteristics wrt temp:

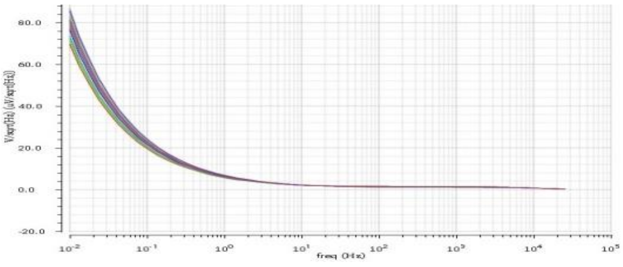

Figure 9: Parametric Noise characteristics wrt temp**:**

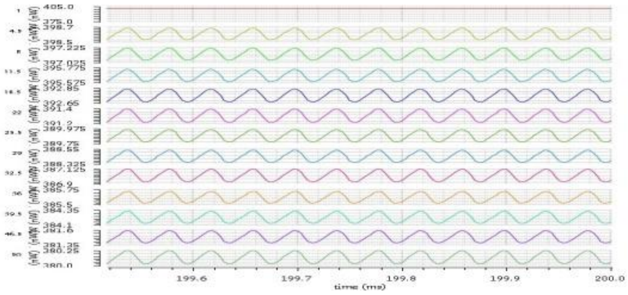

Figure 10: Parametric power characteristics wrt temp

Table 3: Comparative Analysis Of Previous Work & Proposed Bio-OTA

Reference	29	30	31	32	33	34	35	**This work**
Year	2008	2009	2014	2014	2015	2017	2017	**2018**
Tech(ɳɱ)	90	90	90	90	90	90	90	**90nm**
Vdd (V)	3	3	1.2	1	1	0.5	1.8	**1 V**
Power(µW)	30	**35.5µA**	852	2.6	0.005	0.021	261	**0.390µW**
Noise (µV/√Hz)	2.3	0.0514	0.0349	0.138	--	--	--	**1@100Hz** **0.82@10KHz**
Gain(đB)	39.9	**2500 V/V**	59.8	55	31	48	66	**≈ 76dB [Flat]**
GBW(Hz)	3.8M	--	348M	15.3K	52K	29K	51M	**223.6MHz**
CMRR (đB)	--	140	---	131	--	--	--	**> 75.65dB**
PSRR(đB)	--	--	--	70	--	--	--	**> 90dB**
NEF	--	8.5	--	--	--	--	--	**1.5**
PEF	--	216	--	--	--	--	--	**2.25**
PM^{O}	80	--	62.2	69.46	69	61	103.4	**> 45^{0}**
Pn (watts)	--	--	--	--	--	--	--	**4.14e^{-17}**
Pn (dBm)	--	--	--	--	--	--	--	**-133.82**
Ts (^{0}K)	310	--	--	--	--	--	--	**300**
C_L (F)	--	--	--	--	1p	0.5p	30p	**0.5f – 5p**
BW(Hz)	0.1-20k	--	--	--	---	--	---	**0.1-25k**

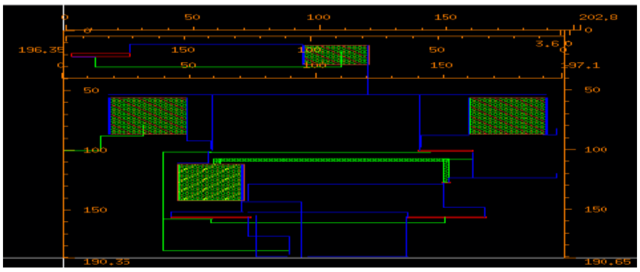

Figure 11: OTA Layout

5. Conclusion

High gain Bio-OTA consuming low power and exhibiting low noise characteristics is designed in 90nm CMOS technology. The amplifier achieved 76 dB gain by consuming 390nW power. The input referred noise of Bio-OTA is 1µ**V/√Hz** and 828n**V/√Hz** at 1Hz and 10 KHz respectively. The obtained CMRR and PSRR are about 75dB and above 90dB respectively. The designed Bio-OTA is used for neural signal recording applications

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