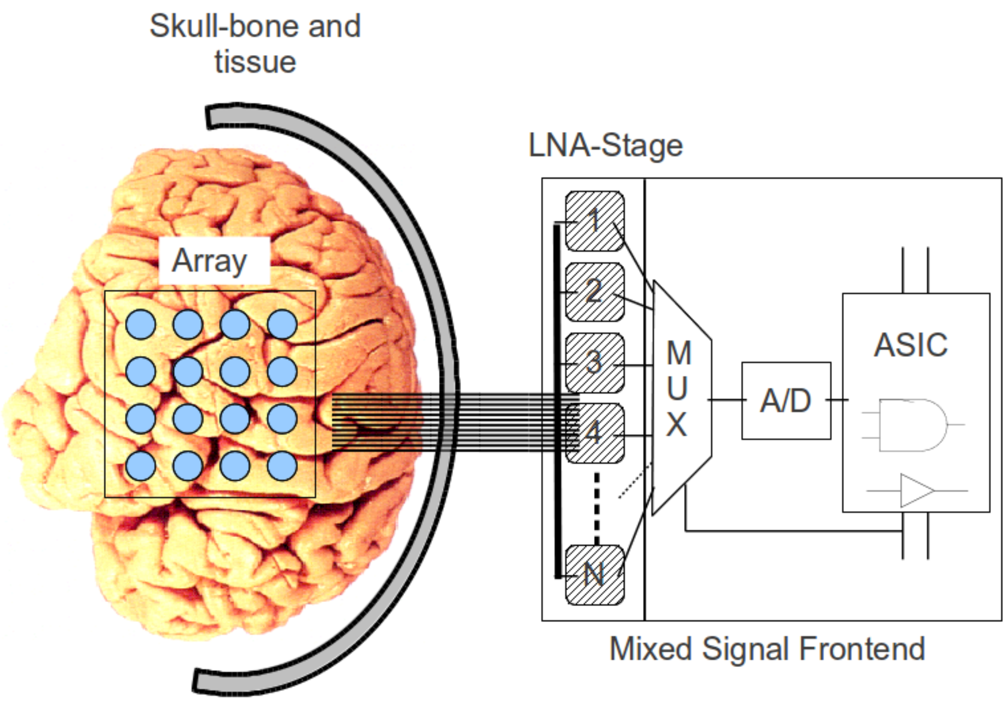
Project Report

Band-pass filter for a neurological signal acquisition system



Group number:

Mohd Shahedur Rahman (CMM, 6088714)

Contents

1. **Introduction** 3
   1.1. Local Field Potential 3
   1.2. Action Potential 4
2. **Description of the amplifier topology** 4
3. **Design of the OPAMP** 5
   3.1 Choosing the Inversion Coefficient – IC 5
   3.2. Choosing Length 5
   3.3. Bias Circuit 6
   3.4. Miller OTA 7
   3.5. Common Source Amplifier 7
4. **Compensation Network** 7
   4.1. Theoretical background 7
   4.2 Compensation 8
5. **Feedback Loop** 9
6. **Noise** 10
7. **Area Calculation** 10
8. **SIMULATION RESULTS** 11

1. Introduction

The main objective of this project is to design a filter that can collect neurological signals from two different types with different amplitude and frequency ranges, namely Low Field Potentials and Action potential or Spikes. The band pass filter is created using an Operational amplifier (OP-AMP) with a combination of low pass and high pass feedback. The system includes various components such as an electrode array for signal recording, several low noise amplifiers for amplification, multiplexers and A/D converters for digitalization, and a digital ASIC for pre-conditioning and signal processing. To minimize noise interference on each node, each electrode is linked to a single low noise amplifier.

A detailed illustration of the overall neural signal processing flow can be found in Figure 1.1.

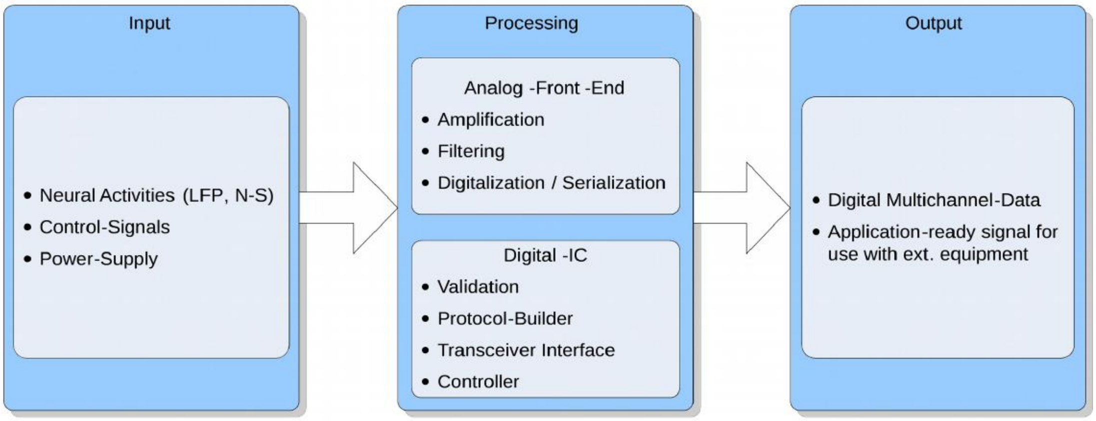


Fig 1.1: Sketch of signal flow for recording and processing neural signals

1.1 Local Field Potential

Low Field Potentials (LFPs) are commonly captured using electrical contacts that are significantly larger than the power sources created by individual neurons. For instance, a typical electrical contact used in Deep Brain Stimulation (DBS) lead implantation surgery for target identification has a cylinder shape with a 1 mm length, 1.27 mm diameter, and a surface area of 1.99mm^2. In comparison, microelectrodes have electrical contacts that are much smaller, with an area of approximately 4.02 x 104mm^2, and are used for microelectrode recordings in a tissue volume of 0.065mm^3. This indicates that microelectrodes transmit action potentials from a small group of neurons, while LFP recordings capture the total activity of the dendrite tree potentials that involve thousands of neurons. These signals have a frequency range of 1 to 250 Hz and an amplitude of less than 5mV.

1.2 Action Potential

An action potential is a signal that occurs when the membrane potential of an axon rapidly changes, either by rising or falling. The transmission of action potentials plays a crucial role in the functioning of the brain, as it allows the nervous system to relay information to the central nervous system and execute commands from the central nervous system to the peripheral regions. These signals have a frequency range of 1 to 10 kHz and an amplitude ranging from 50 to 500µV.

The system that needs to be developed consists of two components. The first part is a low noise amplifier that achieves the low pass characteristic. The second component is a feedback system that includes a high pass filter designed to suppress low frequencies, which ultimately produces the required bandpass characteristic. The subsequent chapter illustrates how these two parts are designed while adhering to the given restrictions.

2. Description of the amplifier topology

The operational amplifier is composed of two amplifier stages. The first stage is the differential amplifier, while the second stage is the common source amplifier. In Figure 1, the differential amplifier includes a p-type differential input pair (M1 and M2) and an n-channel M3 output, with current mirrors M4 and M5. The common source amplifier, with an active load consisting of M6 and M7, provides gain.

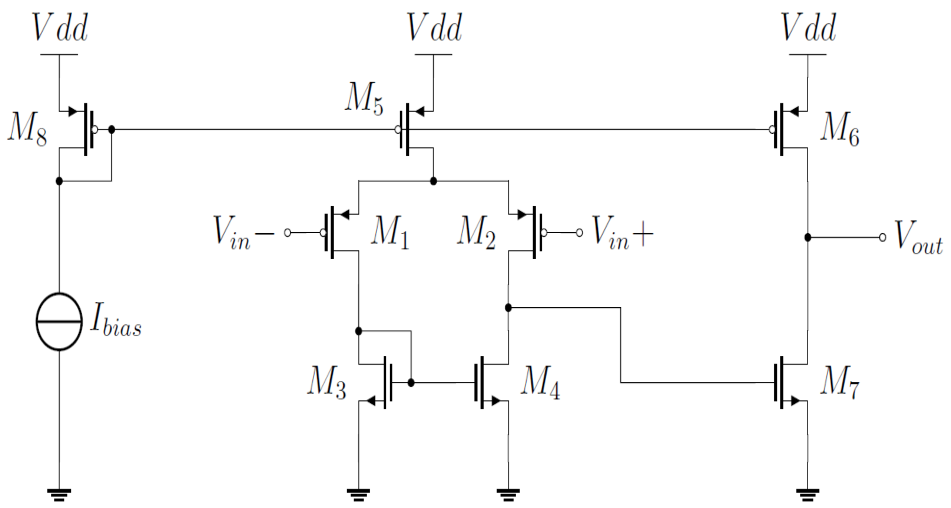


Fig 2.1: Circuit Diagram of 2-stage amplifier

The Miller Operational Trans-conductance Amplifier (OTA) is the first stage, converting the differential input voltage signal to a voltage-controlled current source. The OTA is important for building analog filters and can also be used as a low-pass filter. The Common Source amplifier, the second step, converts the current into voltage (V_{out}). In the circuit, M8, M5, and M6 create a current mirror, supplying the bias current for the differential amplifier circuit and the common source amplifier. M3 and M4 form another current mirror to ensure that a uniform current flows through the differential combine branches. Additionally, the Miller compensation circuit, consisting of electrical condenser CC and electrical device RC, improves the phase margin of the OTA.

3. Design of the OPAMP

To implement the circuit, the design process is divided into three components. The first component involves determining the transistor dimensions using the $\mathrm{g_m/I_d}$ methodology. This methodology provides a unified view of the transistor's operating point, regardless of its dimensions, by focusing on the inversion coefficient and trans-conductance efficiency. Therefore, to obtain other parameters, only IC, Id, and L values need to be identified. The "ams35_cmos_gmId_plots" is used as a reference to model the transistors in this project.

3.1 Choosing the Inversion Coefficient – IC

The inversion coefficient is a numerical measure of the channel inversion, which is a normalized number that is proportional to the quantity of free carriers in the channel region. Weak and moderate inversions are used for low-voltage and low-power applications. The selection is summarized in Table 3.1

MOSFET	IC	Reason
PMOS	5	Higher inversion for low gain
NMOS	3	Moderate inversion for high pairs

Table 3.1: Selection reasoning of Inversion Coefficient

3.2 Choosing Length

We know that decreasing the output resistance increases the current. From the plot "ams35_cmos_gmId plots" file, we have 2 choices of Lengths, which are 350 nm and 550 nm. For Moderate cut-off frequency, moderate area good matching, we choose

$$L = 2 * L_{min}$$

For $L_{min} = 350nm$, We chose 350nm and 550nnm.

MOSFET	L	Reason
PMOS	350nm	Higher Current
NMOS	550nm	Lower Current

Table 3.2: Length of MOSFETs

3.3 Bias Circuit

To provide a steady current flow through the OTA, a bias circuit is needed. This is realized by constructing a current mirror. To find the appropriate bias current, an estimation is done based on the slew rate. Since there are two different types of signal at varying frequency ranges, the slew rate would be:

$$SR_1 \approx V_{peak} * 2 * \pi * f_{max}3 \approx 5mV * 2 * \pi * 250Hz \approx 8V/s$$

$$SR_2 \approx V_{peak} * 2 * \pi * f_{max} \approx 500\mu V * 2 * \pi * 10KHz \approx 31V/s$$

Where V_{peak} is the Peak Voltage of the Signals given as input & in this case for:

Local Field Potentials (LFP) is 5mV

Neural Spikes is 50µV to 500µV

If the higher value Slew Rate is chosen, the required current will be:

$$I = C_L * SR = 200pF * 31 = 6.2nA$$

We judge that this current is too small, so we decided to use a bigger flow of current. We use I = $10\mu A$. This makes the slew rate bigger, and we expect the Slew Rate value to be around SR ≈31KV=s.

To maintain the supposed Slew Rate, I must flow at least in the output branch, which means

$$Id_{M6} = I = I_{bias} = 10\mu A$$

The maximum allowed current is as follows:

$$I = \frac{P_{max}}{V_{max}} = \frac{180\mu W}{3.3V} = 54\mu A$$

To avoid unwanted problems and to simplify the ratio, instead of $10\mu A$, we allocate the same current to all branch of the bias circuit. Thus:

$$I_{Bias} = Id_{M5} = Id_{M6} = Id_{M8} = 10\mu A$$

Which totals to $30\mu A$, way below the maximum current.

3.4 Miller OTA

Similarly, using the steps mentioned previously, the length (L) and IC is chosen appropriately for the following transistors. Since the gain A1 (OTA) is proportional to the trans-conductance of transistor (M2), a higher gm2 gives a higher gain. As seen in the gmid plots provided, a lower IC for M2 gives a higher gm2 but gives a higher value for transistor' s width. Following are the values chosen for the respective transistors. The length for M3 and M4 have been increased too in order to get a very good matching but increases the transistor area.

3.5 Common Source Amplifier

Finally, the IC for M7 is chosen to operate in the moderate region. Secondly, a lower IC gives a higher gain A2 since it gives a higher value of gm7. Below is the values for all total seven total seven transistors.

The calculated parameters of all transistors used are shown in Table 3.3

MOSFET	IC	Id	W	L	Id/W	Gm/Id
M1	5	5 μA	2.27 μm	0.35 μm	2.2 A/m	11.15
M2	5	5 μA	2.27 μm	0.35 μm	2.2 A/m	11.15
M3	3	5 μA	10 μm	0.55 μm	0.5 A/m	13.26
M4	3	5 μA	10 μm	0.55 μm	0.5 A/m	13.26
M5	5	10 μA	4.54 μm	0.35 μm	2.2 A/m	11.15
M6	5	10 μA	4.54 μm	0.35 μm	2.2 A/m	11.15
M7	5	10 μA	20 μm	0.55 μm	0.5 A/m	13.26
M8	3	10 μA	4.54 μm	0.35 μm	2.2 A/m	11.15

Table 3.1: Parameters of MOSFETs

4. Compensation Network

4.1 Theoretical background

The op-amp consists of a network connected to provide a negative feedback. This negative feedback ensures the output is stable, free from fluctuations. The input signal has to propagates around this feedback loop. The signal travels from input through the op-amp to the output. From the output the signal is fed back to input through the feedback network. During this signal propagation a sequence of delays are introduced based on the output impedance characteristics.
If these delays add up to change the phase lag by 180°, the feedback changes from negative to positive. In addition if this positive feedback results in a gain of more than 1, there will be regenerative build-up in the signal which will result in instability.

In terms of the transfer function of the op-amp. which can be given by the following expression:

$$H(s) = \frac{A}{1 + \beta A}$$

If $1 + \beta A$ is 0, the transfer function will theoretically equal infinity. The frequency at which this occurs is called the pole. In practice, because of finite characteristics of op-amp power supply, the op-amp output will be unstable. This occurs when the output of op-amp is capacitive in nature. As a capacitive load introduces additional pole where negative to positive feedback conversion occurs. This causes oscillations and ringing effects at the output.
Additional components are added to the circuit to prevent this instability and is called compensation.

4.2 Compensation

To separate the dominant and non-dominant poles in a two-stage amplifier, a compensation capacitor Cc, also known as Miller capacitor, is required. Adding this capacitor makes lower frequency to more lower value and high frequency to more higher value but this also adds an unwanted zero. Cc is bidirectional, and the feed-forward path results in zero. To compensate, the feed-forward line should be cut by connecting the capacitor to a resistor RC. The following formulas were used to calculate the values for RC and compensator capacitance Cc:

We have to first select an initial value for the compensation capacitor that will shift the unity gain frequency at the second pole. i.e.

$$Cc' = \beta \left(\frac{gm1}{gm7}\right) * CL$$

here β is equal to 1 (For unity gain) and from section 3.5,

$$gm_1 = 57.5$$
$$gm_7 = 115$$

therefore,

$$Cc' = 100pF$$

Then we find the phase -51 degree at frequency, ft=404.06 kHz and gain, A=5.17db. Then we get the value of Cc and Rc according to below formula,

$$R_c = \frac{1}{1.7\omega t Cc} \qquad Cc = A * Cc'$$

We should also make sure that the phase margin remains between 40°to 75°for system stability. There-fore, with R_c constant we iterate over Cc until we reach acceptable phase margin range.
The final values are:

$$R_c = 50K\Omega$$
$$Cc = 15pF$$

The performance of our Miller OTA circuit with compensation is summarized in Table 8.1. And the Plot is shown in Figure 6.1

The Miller OTA schematic with compensation circuit is shown in Figure 4.1

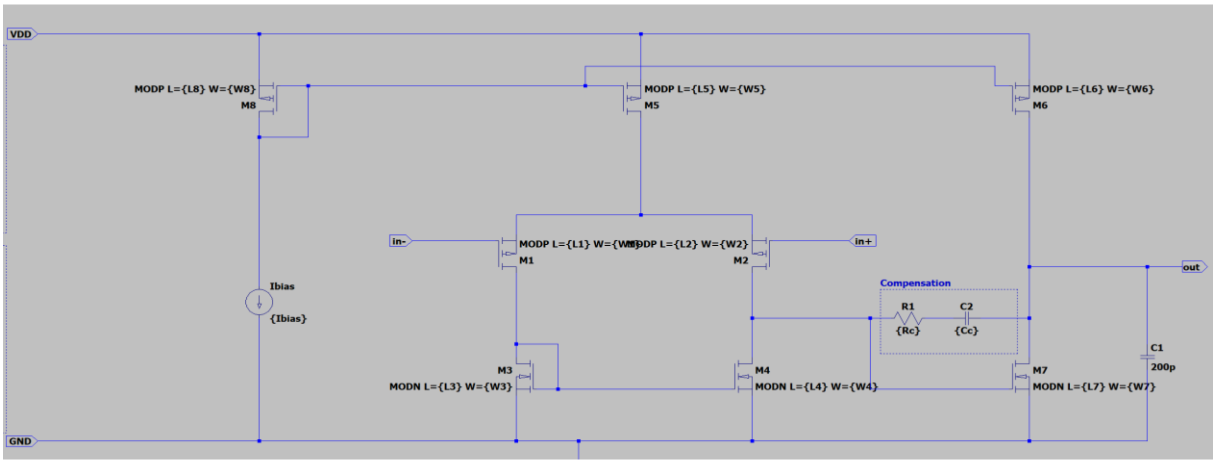


Fig 4.1: Miller OTA schematic

5. Feedback Loop

For better gain we consider a negative feedback circuit. The feedback circuit for the opamp will be an RC circuit.
The feedback capacitor C_f is related to the input capacitance C_{in} with the following relation:

$$C_{in} \geq 100 * C_f$$
$$C_{in} = 15pF$$

Therefore,

$$C_f = 150fF$$

The feedback resistance R_f is related to the feedback capacitor C_f with the following equation.

$$R_f = \frac{1}{2\pi C_f F_{3db1}}$$

Which gives $R_f = 1.06T\Omega$

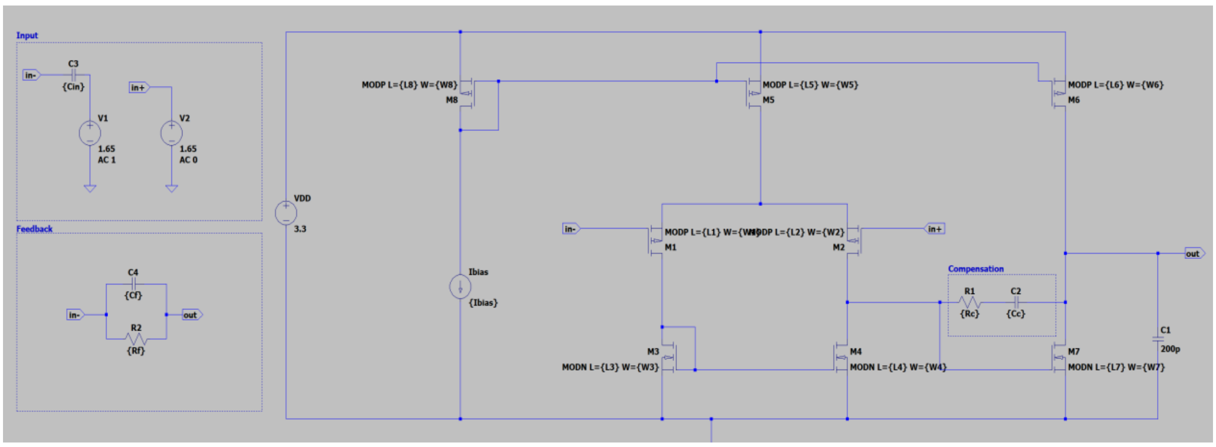


Fig 5.1: Miller OTA with Band pass filter

6. Noise

For noise examination, as it were the commotion of MOSFETs is considered since the resistors and capacitors are considered to be in a perfect state. MOSFETs create two sorts of commotions i.e. warm and flicker noise. Warm noise is prevailing in higher frequencies whereas flash commotion is prevailing in lower.

7. Area Calculation

MOSFET	W	L	Area(μm^2) =L*W
M1	2.27 μm	0.35 μm	0.7945
M2	2.27 μm	0.35 μm	0.7945
M3	10 μm	0.55 μm	5.5
M4	10 μm	0.55 μm	5.5
M5	4.54 μm	0.35 μm	1.589
M6	4.54 μm	0.35 μm	1.589
M7	20 μm	0.55 μm	11
M8	4.54 μm	0.35 μm	1.589

Table 7.1: Area Calculation

Area Total = $\sum Area(M_1 \; to \; M_8) = 28.35\mu m^2$

8. SIMULATION RESULTS

8.1 Open-Loop Miller OTA

8.1.1 Gain and Phase Margin

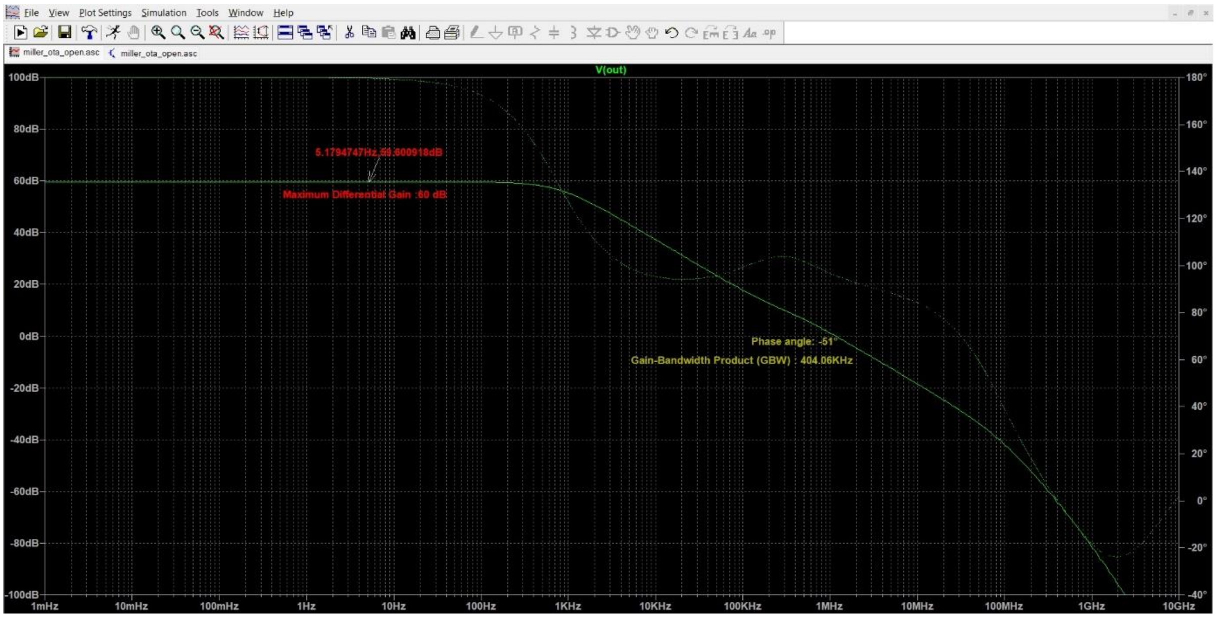


Fig 8.1: Frequency Response of the Open Loop Miller OTA

8.1.2 PSRR

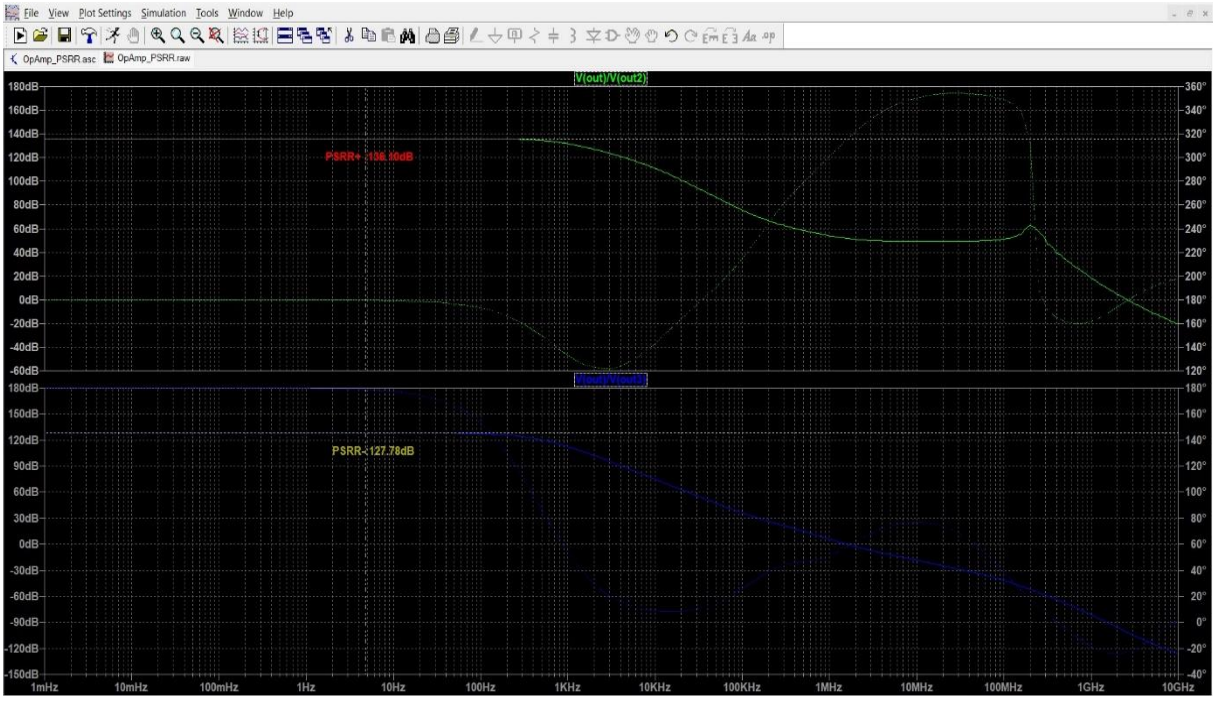


Fig 8.2: PSRR+ and PSRR- of the Open Loop Miller OTA

8.1.3 Slew Rate

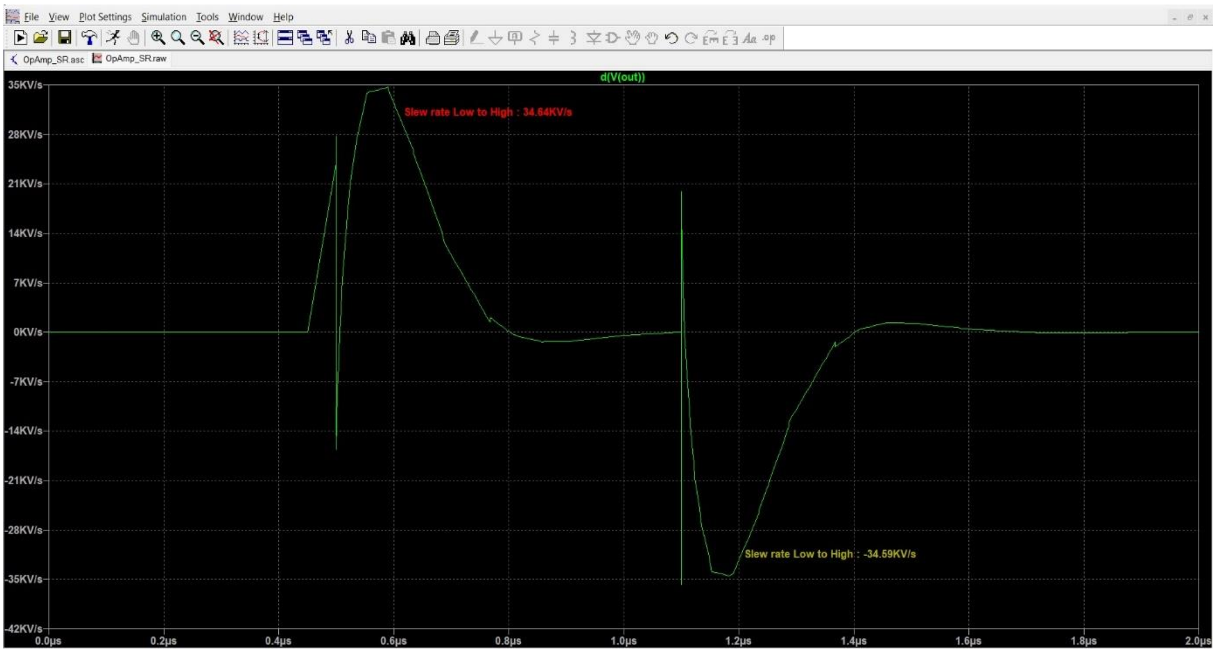


Fig 8.3: Slew Rate (High to Low & Low to High) of the Open Loop Miller OTA

8.1.4 CMRR

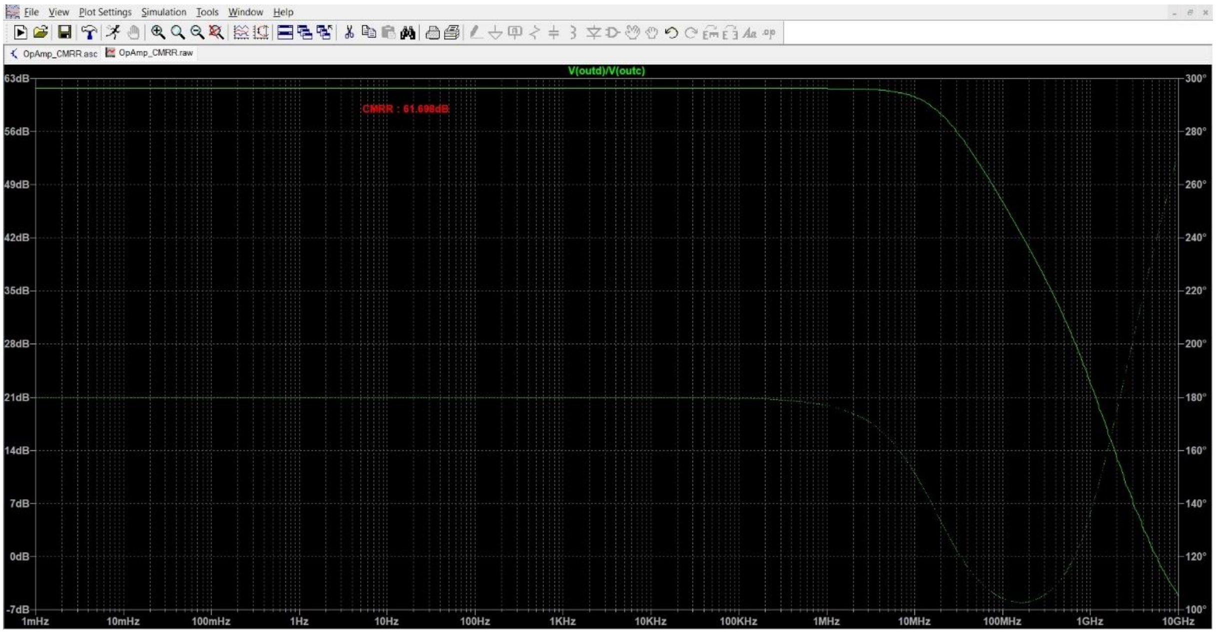


Fig 8.4: CMRR of the Open Loop Miller OTA

8.1.5 Power Consumption

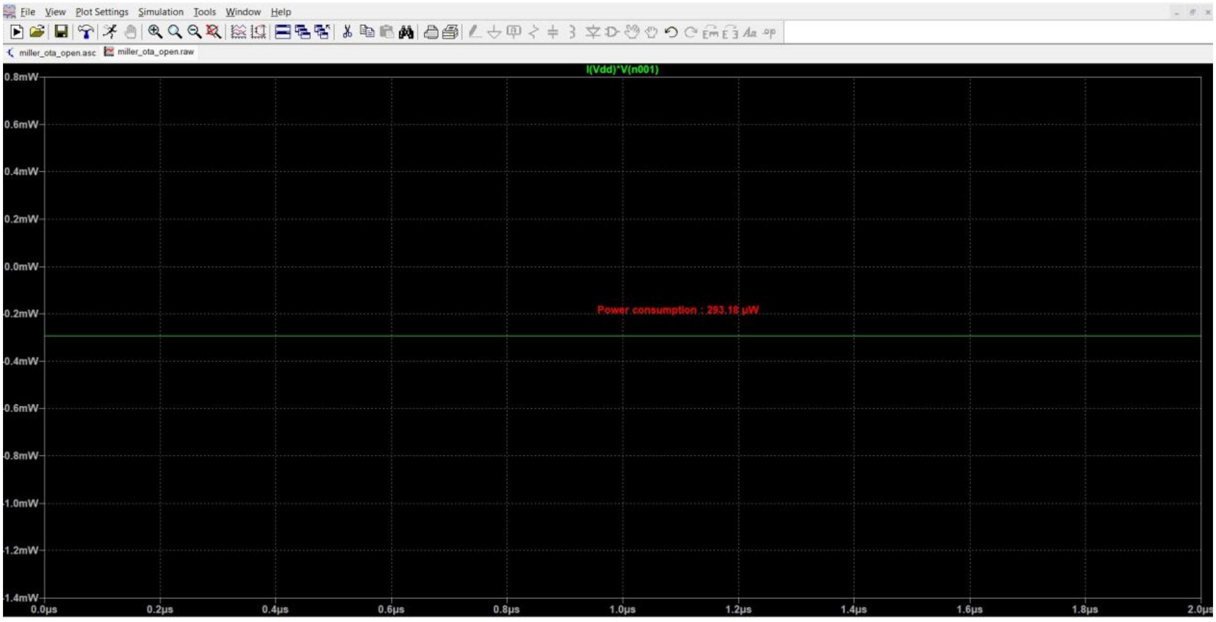


Fig 8.5: Power Consumption of the Open Loop Miller OTA

8.2 Band-Pass Miller OTA

8.2.1 Gain and Phase Margin

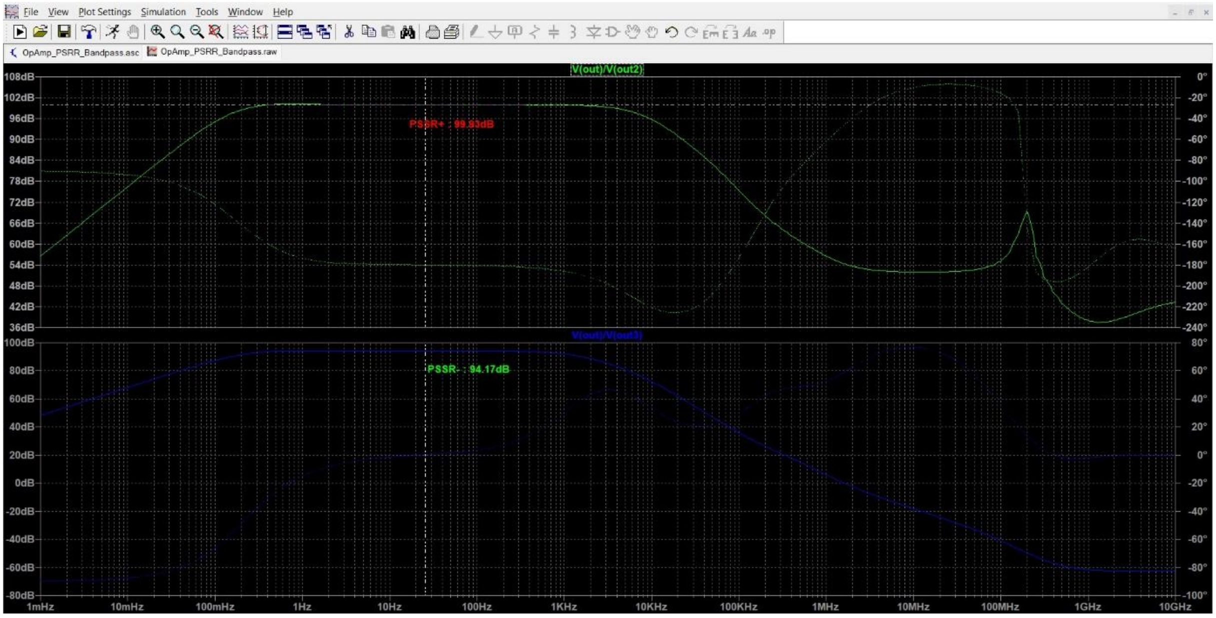


Fig 8.6: Frequency Response of the Bandpass Filter

8.2.2 PSRR

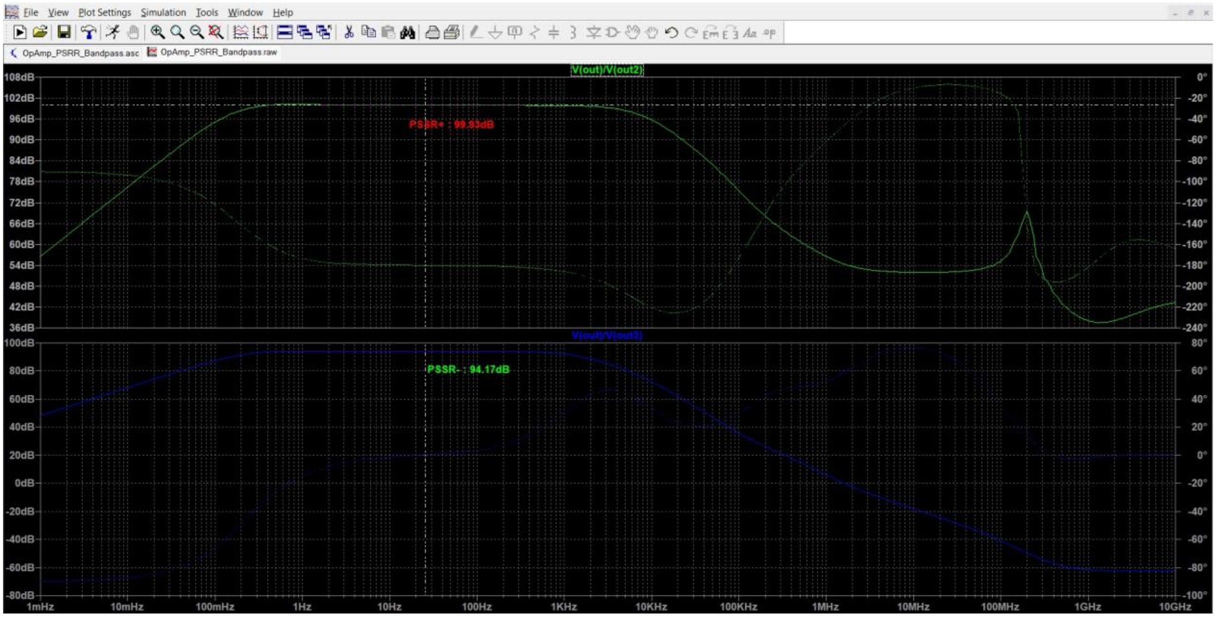


Fig 8.7: PSRR+ and PSRR- of the Bandpass Filter

8.2.3 Slew Rate

Fig 8.7: Slew Rate (High to Low & Low to High) of the Bandpass Filter

8.2.4 Power Consumption

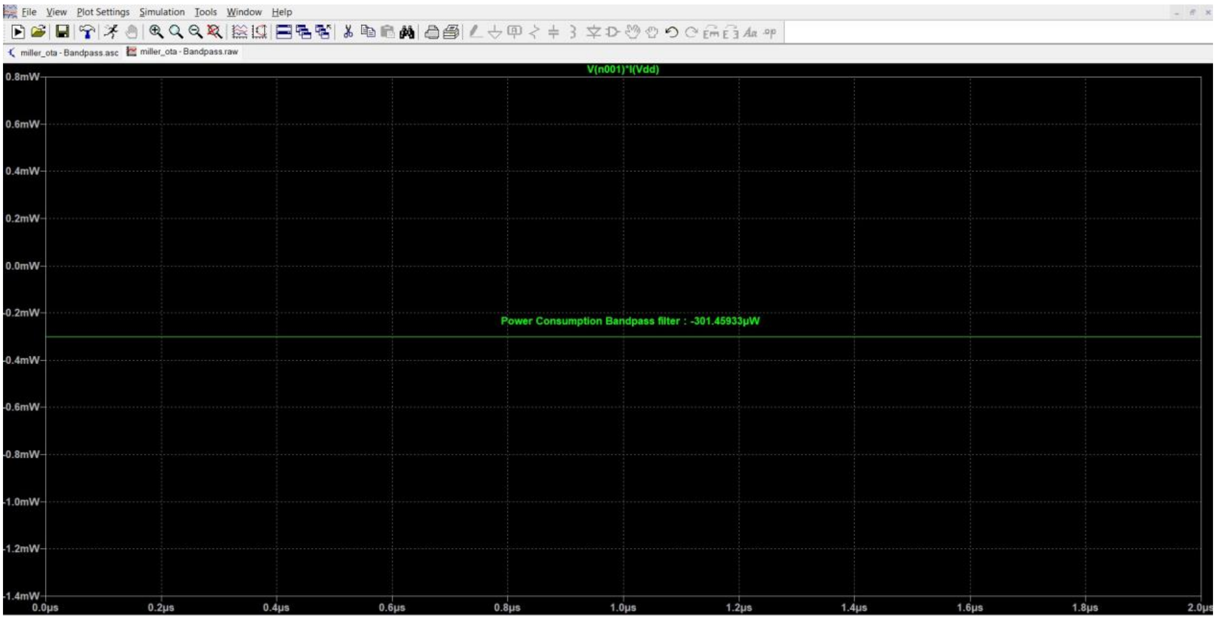


Fig 8.8: Power Consumption of the Bandpass Filter

Performance	Measured Value	Unit
Max. Differential Gain	60	dB
Gain-Bandwidth-Product (GBW)	404.06	KHz
Common Mode Rejection Ratio (CMRR)	61.698	dB
Slew Rate Low-to-High	34.64	KV/s
Slew Rate High-to-Low	-34.59	KV/s
Positive Power Supply Rejection Ratio (PSRR+)	136.10	dB
Negative Power Supply Rejection Ration (PSRR-)	127.78	dB
Voltage at Bias Current Source	2.25	V
Power Consumption	293.18	µW

Table 8.1 Performance of the Miller OTA

Performance	Measured Value	Unit
Max. Differential Gain	39.19	dB
Low Cutoff Frequency	998.25	Hz
High Cutoff Frequency	7.25	KHz
Phase Margin	56	°
Slew Rate Low-to-High	2.85	KV/s
Slew Rate High-to-Low	-2.39	KV/s
Positive Power Supply Rejection Ratio (PSRR+)	99.93	dB
Negative Power Supply Rejection Ration (PSRR-)	94.1739	dB
Voltage at Bias Current Source	2.25	V
Power Consumption	301.45	µW

Table 2 Performance of the Bandpass Filter