BM2013
Analog and Integrated Circuits

Hackathon Report

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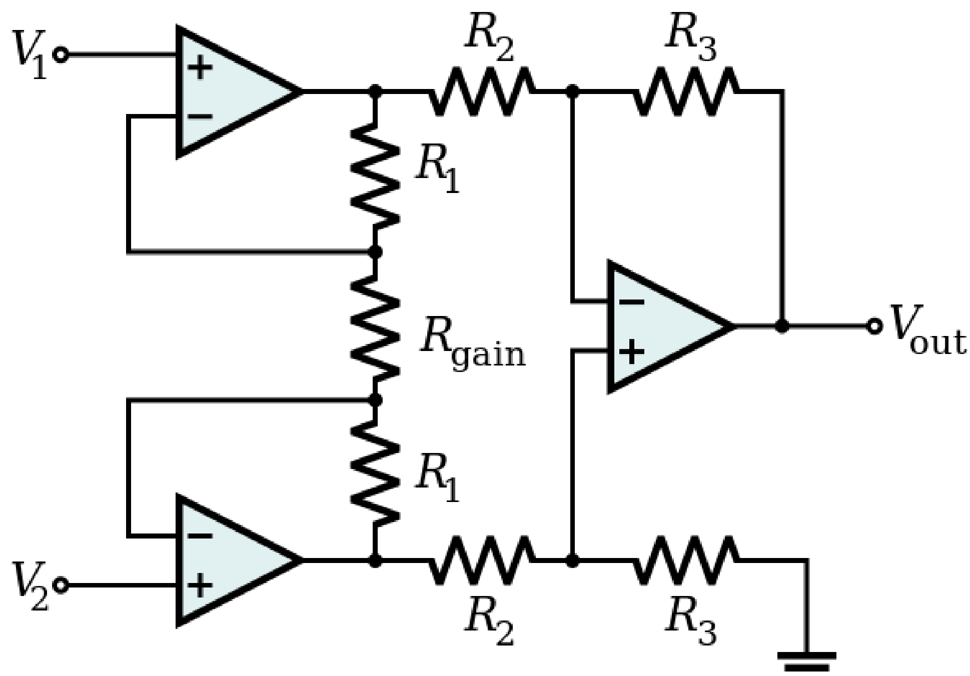
Problem Statement

Design a biosignal amplifier for acquiring ECG signals with the following specifications

- Differential amplifier design (instrumentation amplifier topology)
  - High input impedance (>100MΩ)
  - Low input bias current (<10μA)
  - Low input offset voltage (<100μV)
  - Total gain of 1000 at a bandwidth of 100kHz
  - High CMRR (>50 dB)
  - Supply voltage (up to ±20V)
  - Overvoltage protection
- Band pass filter preferably with Sallen-Key topology:
  - Cut-in frequency: 1 Hz
  - Cut-off frequency: 100 Hz
  - Roll-off rate: >40 dB/decade
  - Minimal pass band ripple
  - Reasonably linear phase response

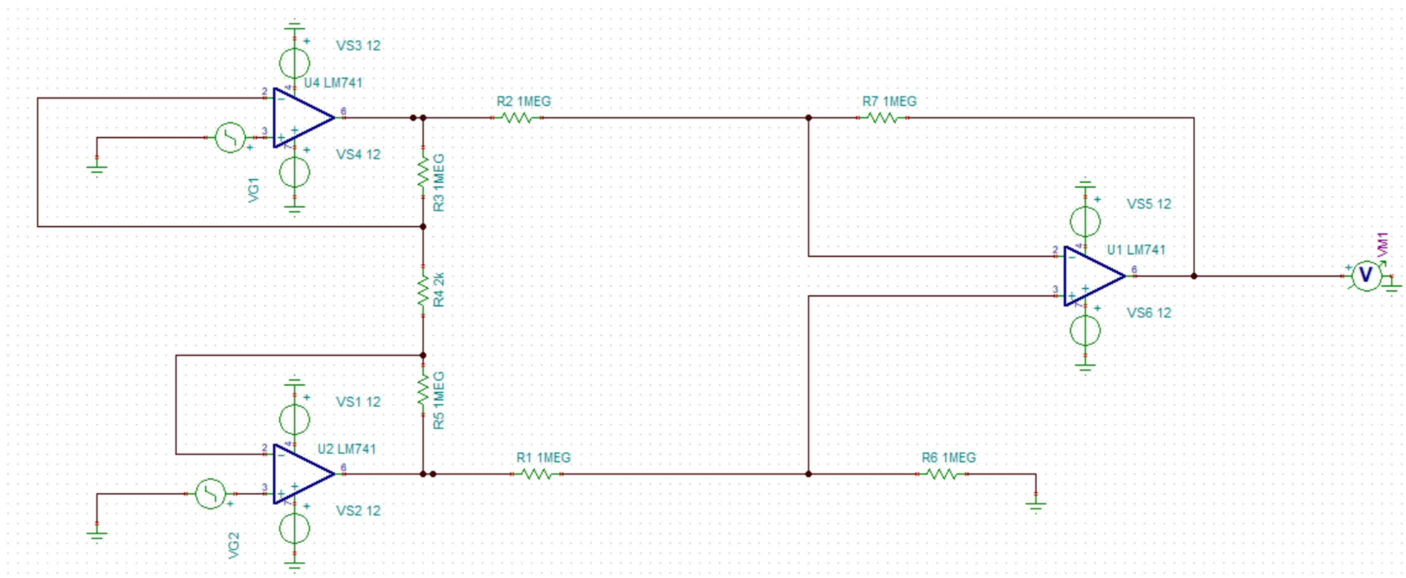
Instrumental amplifier:

An instrumental amplifier is a type of a differential amplifier that has been outfitted with input buffer amplifiers. The characteristics of this type of amplifier are very high open-loop gain, very high CMRR, very low input bias current, and very high input impedance. Therefore these amplifiers are used where great accuracy and stability are required.



For the instrumental amplifier circuit shown above the gain is given by the expression

$$G = (1 + 2 * R1/Rg)(R3/R2)$$

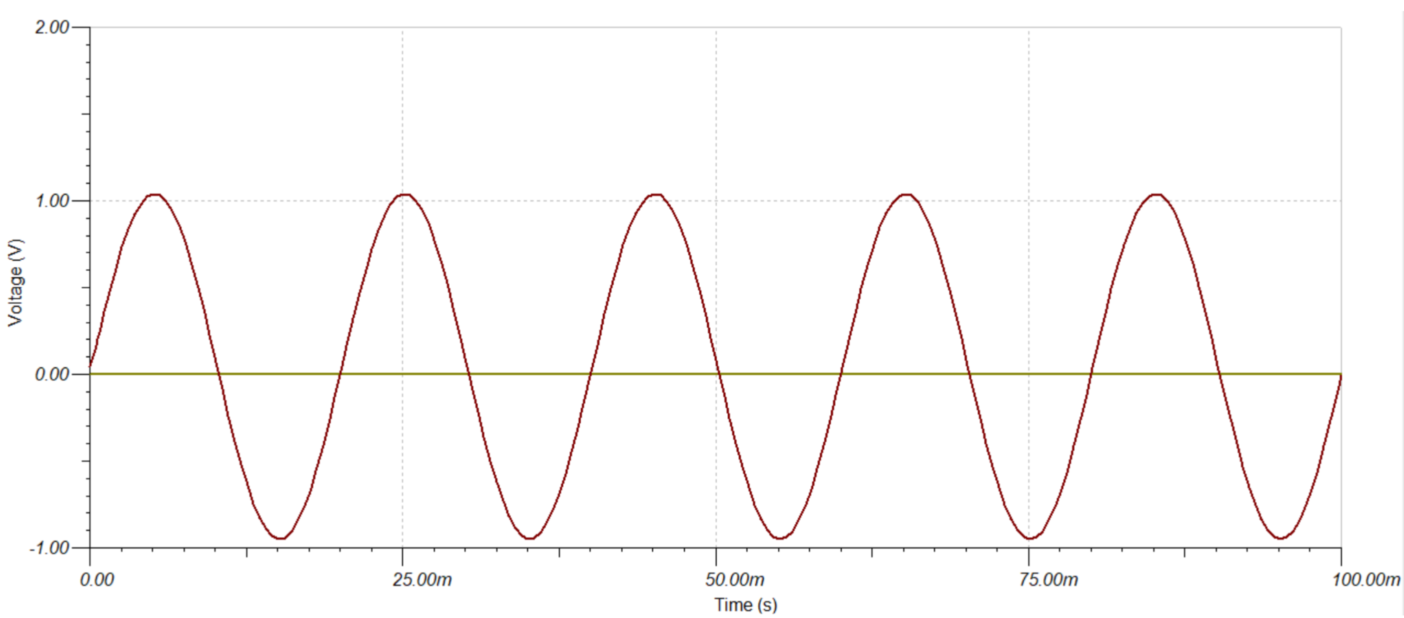


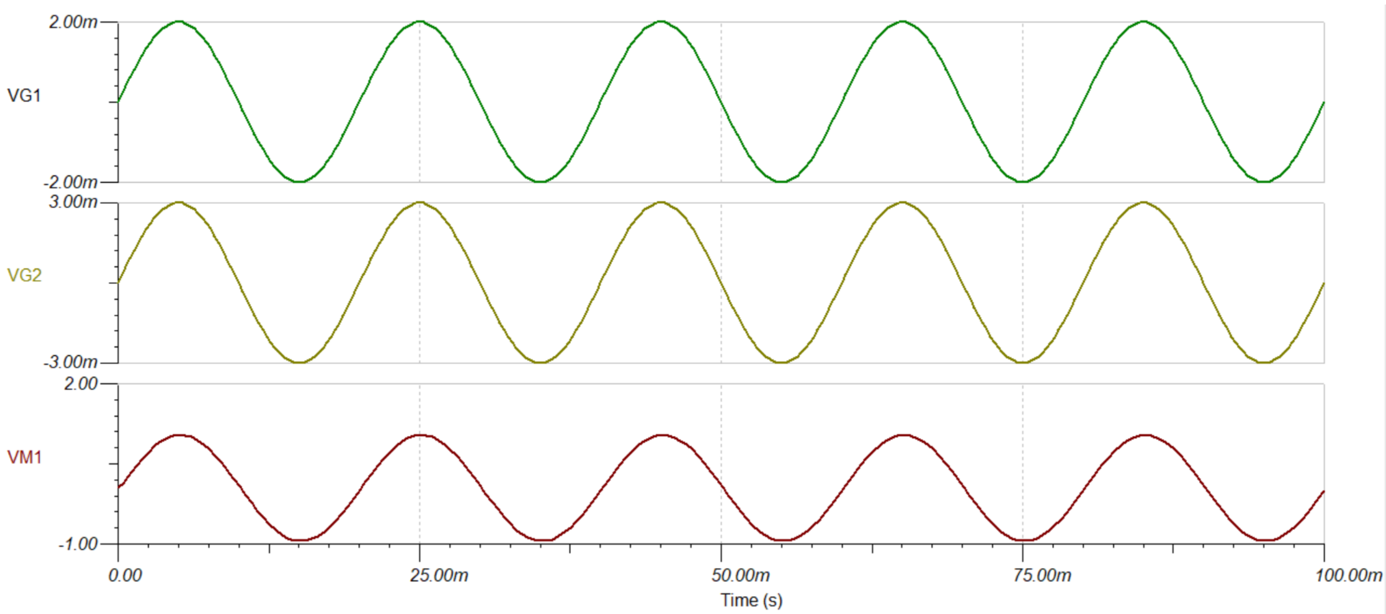
S. No	Quantity	Operation	Label	Value
1	3	Op-amp	U1, U2, U4	LM741
2	1	Input Voltage	VG1	0.002sin(2*pi*50*t)
3	1	Input Voltage	VG2	0.003sin(2*pi*50*t)
3	3	Voltage source	VS4, VS2, VS6	+15V
4	3	Voltage source	VS1, VS3, VS5	-15V

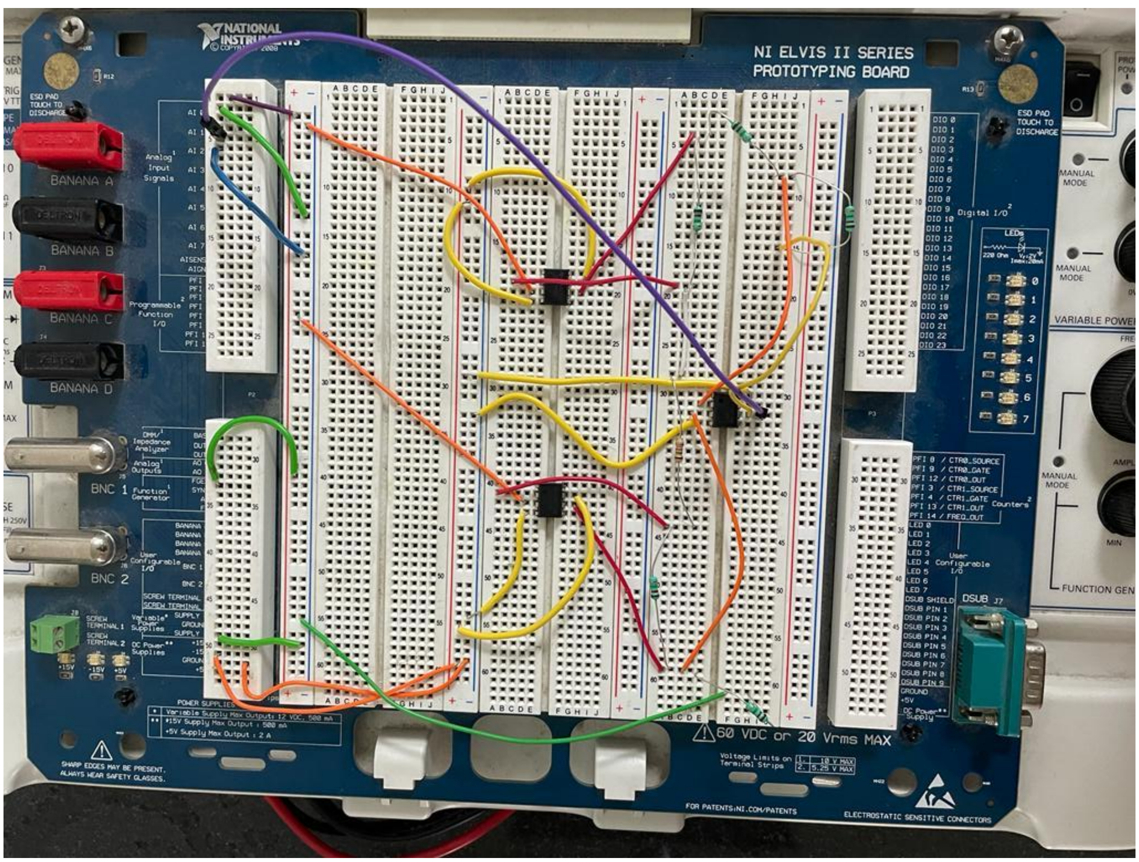
5	1	Voltmeter (for output Voltage)	VM1	-
6	6	Resistance	R1, R2, R3, R5, R6, R7	1MEG
7	1	Gain Resistance	R4	2k

Comparing our circuit with the above theoretical circuit, to get a gain of 1000 we took the values of the resistors R1=1MEG, R2= 1MEG, R3=1MEG, and Rg=2k.

Here, we get the gain G=(1+2*(1MEG/2k))(1MEG/1MEG) =1000







Above we can see that for an input AC voltage with amplitudes 2mV and 3mV, we should get an output voltage of 1V. But we get it as 816mV Thus we can confirm that the gain obtained from the amplifier is 816. It was with an 18.4%

error. It was due to the sensitivity of op-amps and because we didn't divide gain into two factors instead we give the whole 1000 gain in the (1+2*(R1/Rg)) factor. Due to less sensitivity, it didn't give the actual 1000 gain.

Here we also gave the same input 1V in both VG1 and VG2. Ideally, we should get the 0V output but we got 46.04mV as output and this shows there is a Common-mode output voltage of 46.04mV.

Common-mode gain Ac= V_{CMOV}/V_{IN}

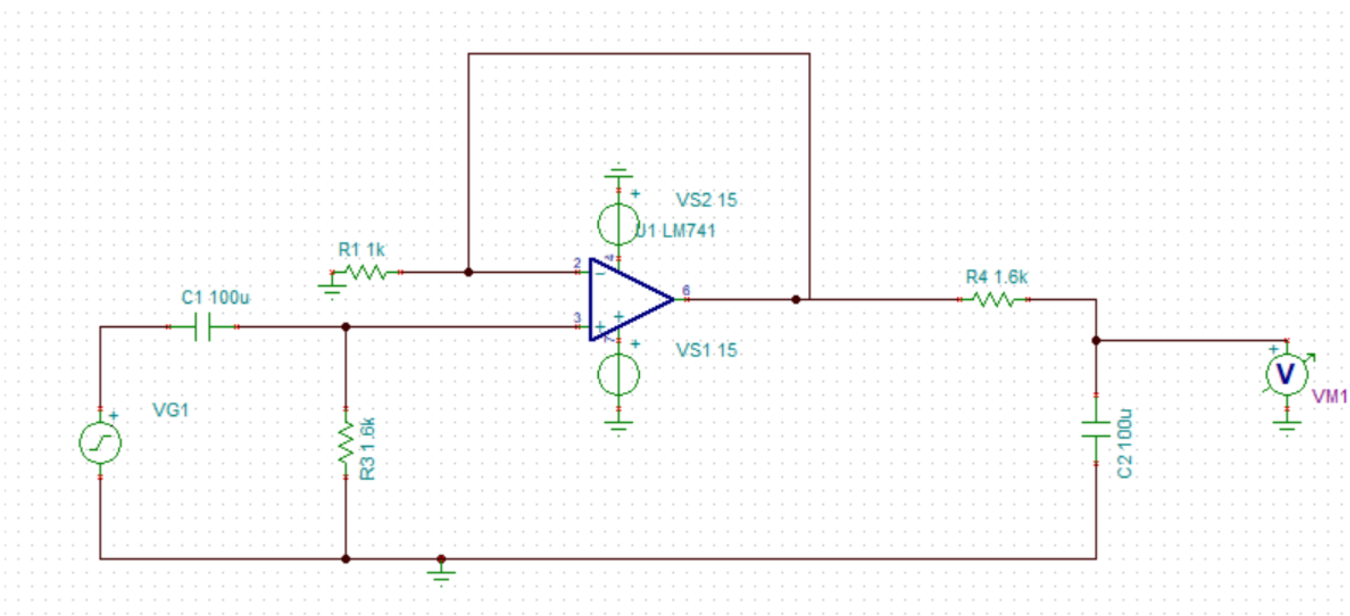
Ac=46.04mV/1V =46.04m

CMRR= 20 log(A_d/A_c) =20log(1000/46.04m) =86.73dB

Hence, the CMRR>50dB

Filter:

A bandpass filter is a device that allows signals within a certain range to pass and rejects others.



Here, we have built and simulated the bandpass filter using the Sallen-Key topology. Sallen-Key topology is an electronic filter topology that is used to build second-order active filters.

In the filter designed above, we took

$R_1 = 1.6\ k\Omega,\ C_1 = 100\mu F,\ R_2 = 1.6\ k\Omega\ and\ C_2 = 1\mu F$ so that the cut in the frequency of the High Pass filter stage would be-

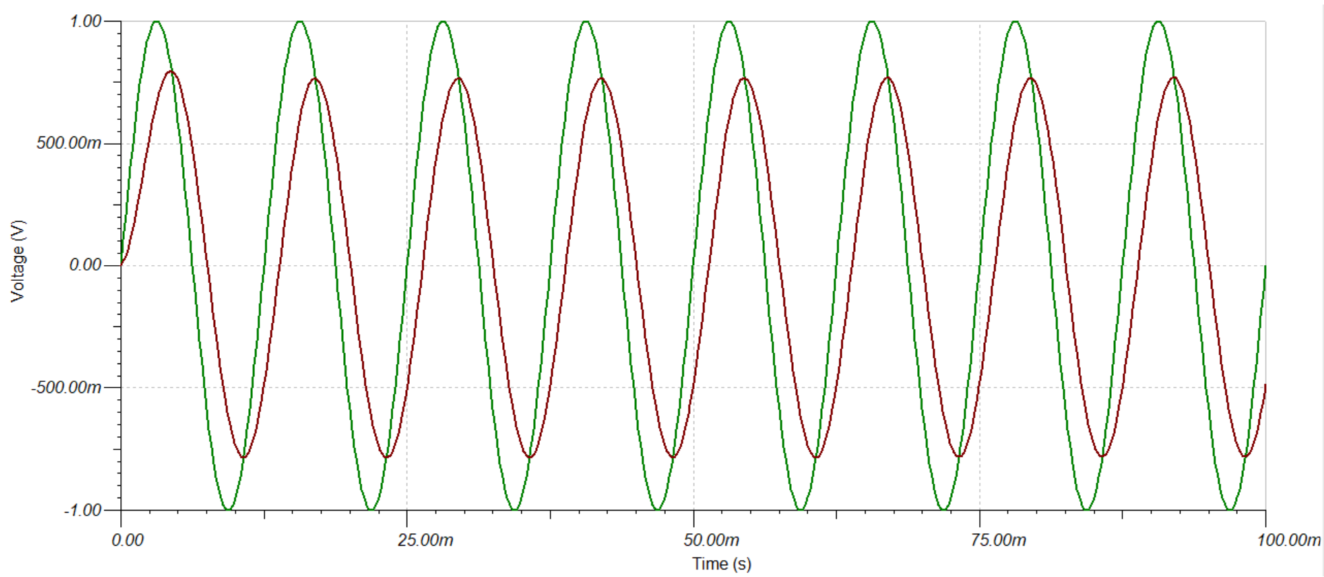
$$f = \frac{1}{2\pi R_1 C_1} = 1\ Hz$$

And the cut off frequency of the Low Pass Filter stage would be-

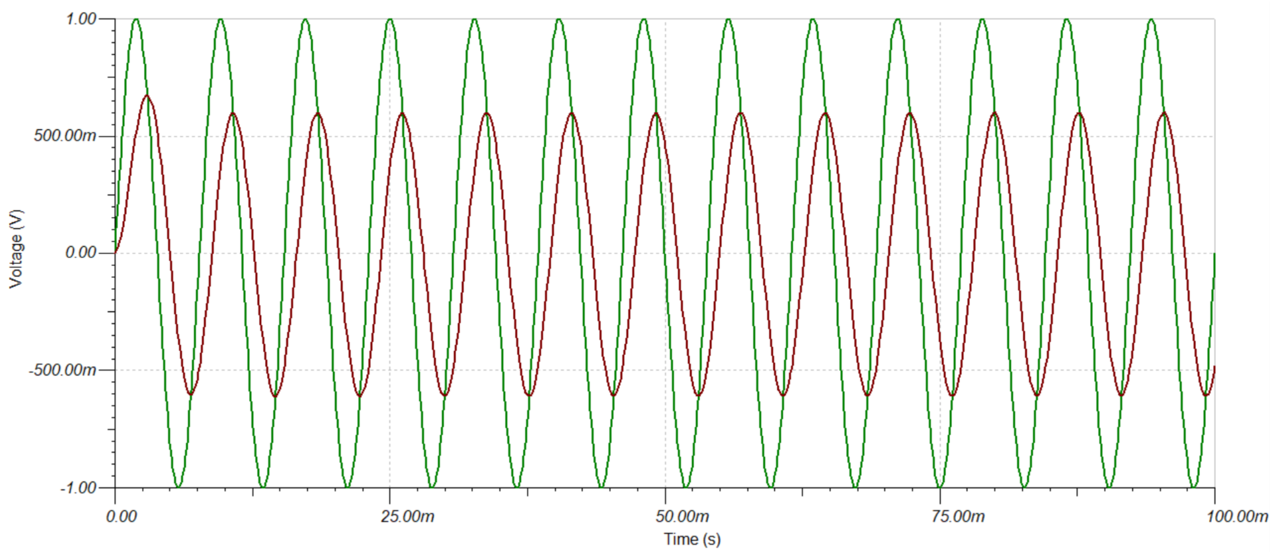
$$f = \frac{1}{2\pi R_2 C_2} = 100\ Hz$$

S. No	Quantity	Operation	Label	Value
1	1	Op-amp	U1	LM741
2	1	Input Voltage	VG1	Checked for various amplitude and frequency
3	1	Voltage source	VS2	-15V
4	1	Voltage source	VS1	+15V
5	1	Resistance	R1	1k
6	2	Resistances	R3, R4	1.6k
7	1	Capacitor	C1	100u
8	1	Capacitor	C2	1u

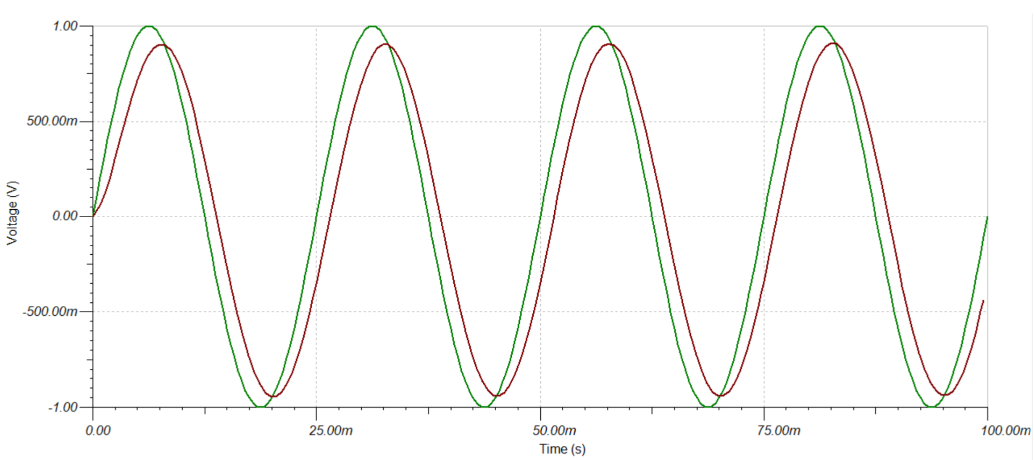
Plot when **f=80Hz**



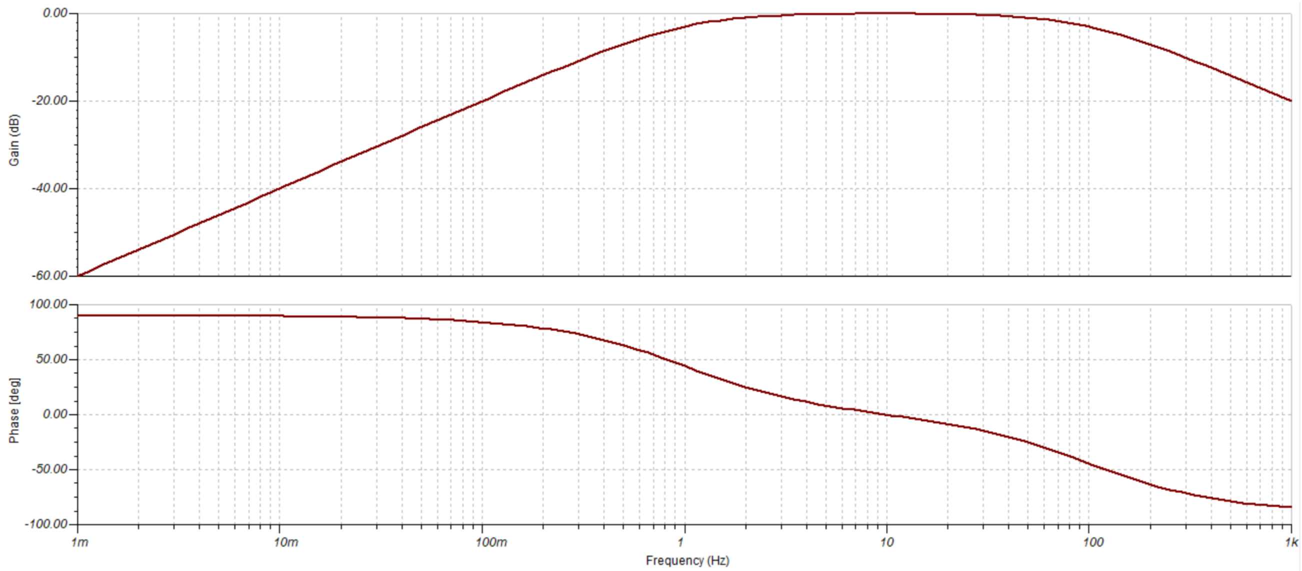
Plot when **f=130Hz**



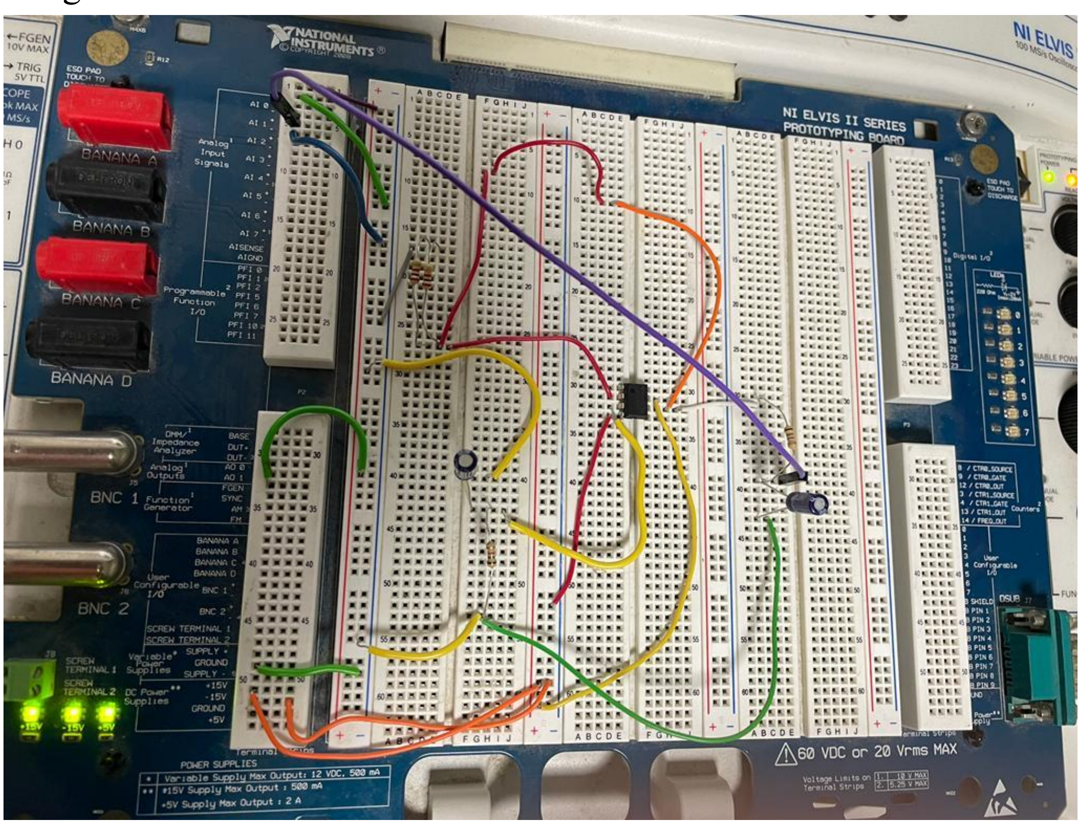
Plot when **f=40Hz**

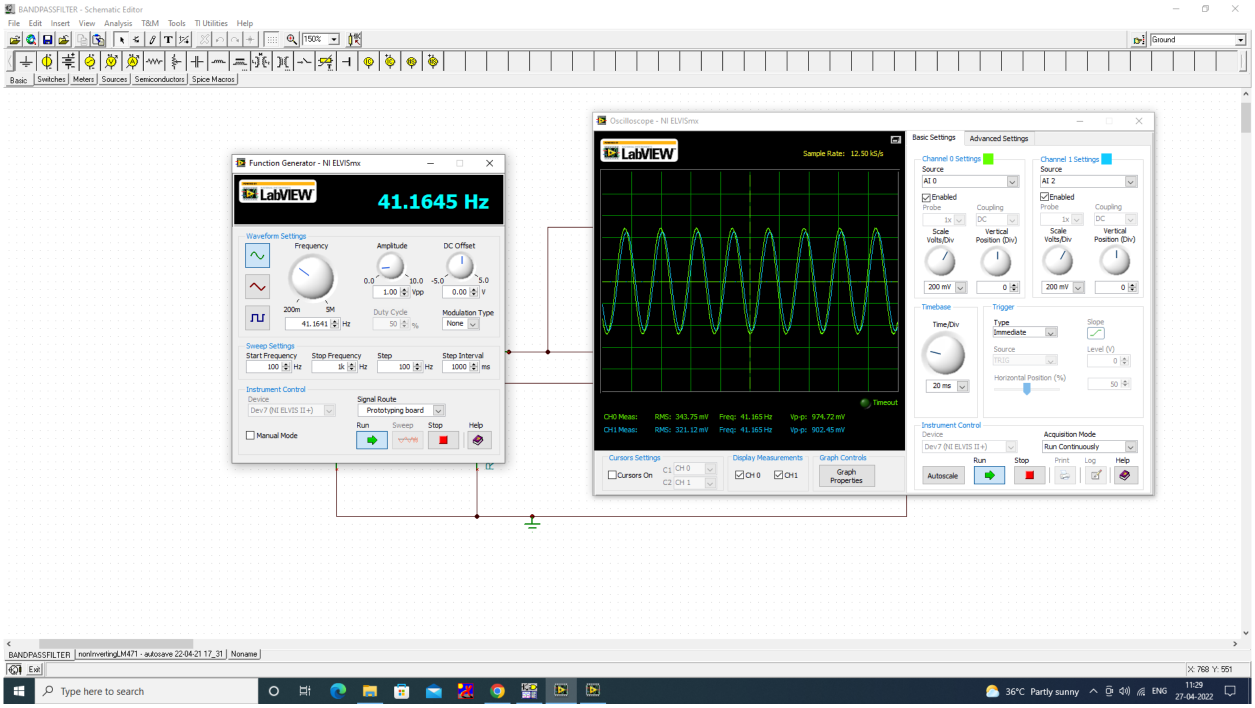


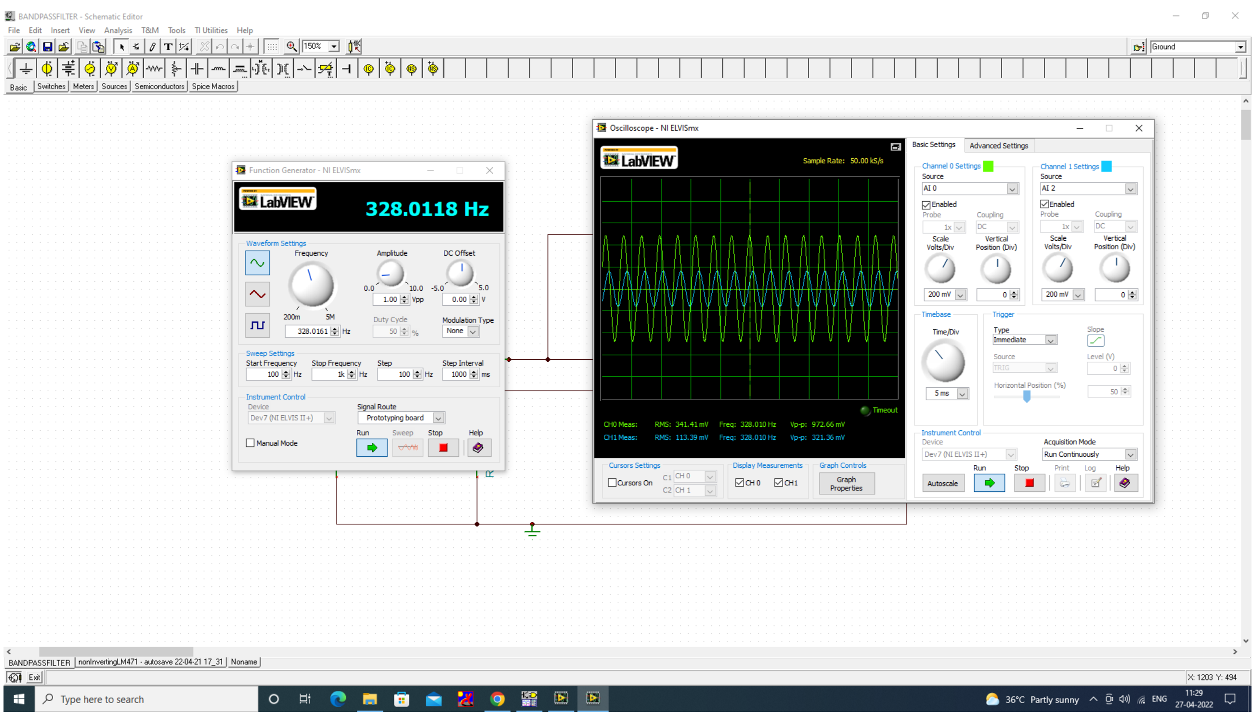
Here, the Bode plot of this filter is



We can clearly see from the bode plot that the cut in frequency is 1Hz and the cut off frequency is 100Hz and the roll of rate is greater than 40 dB/decade. This implies that the filter ignores the signals which have a frequency of less than 1Hz and greater than 100Hz.





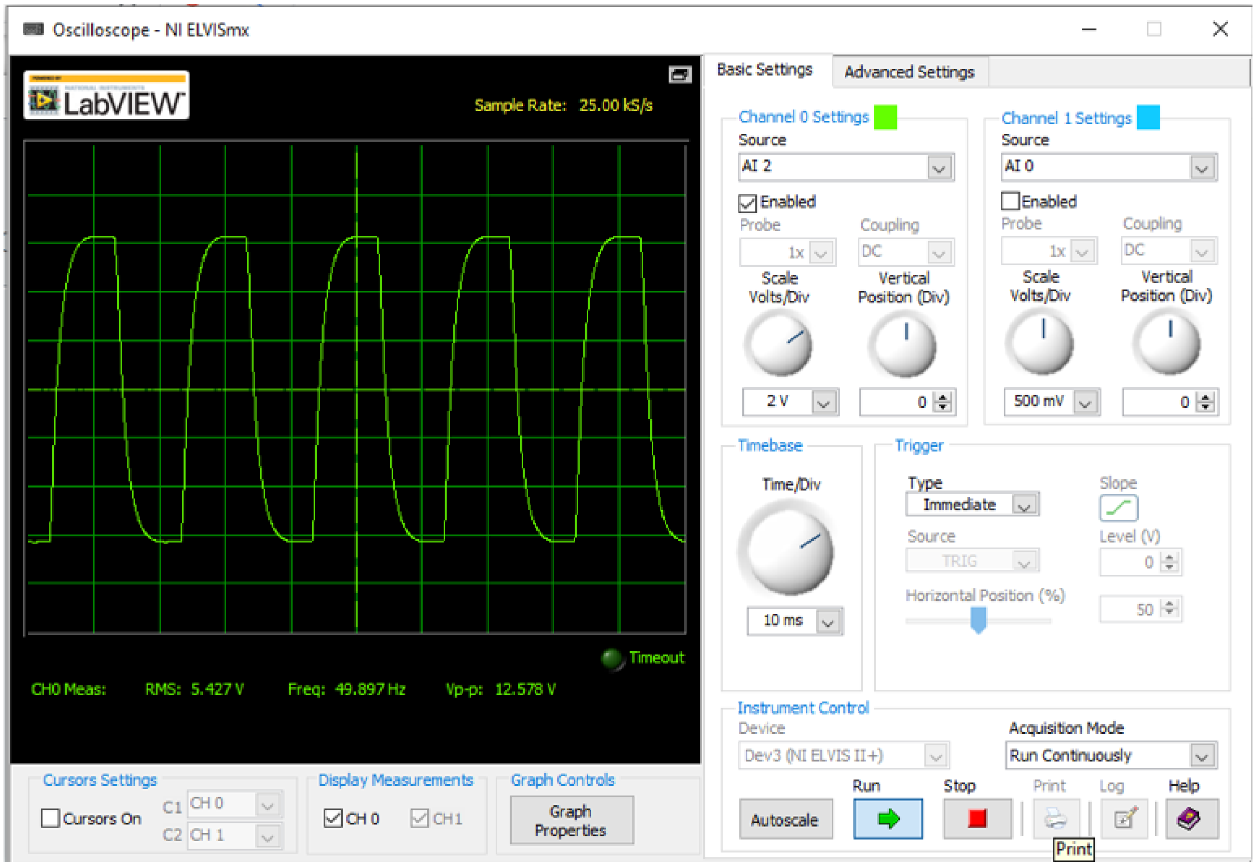


Above, we can see that the filter is rejecting the signals whose frequency is outside the range, i.e., the amplitude of the signals which have a frequency greater than

100 Hz or less than 1Hz is scaled-down, and as we go far below from 1Hz or above 100Hz the amplitude keeps on decreasing, and it tends towards 0.

Based on the observations seen above, we then combined the filter and the instrumental amplifier to amplify the ECG signals.

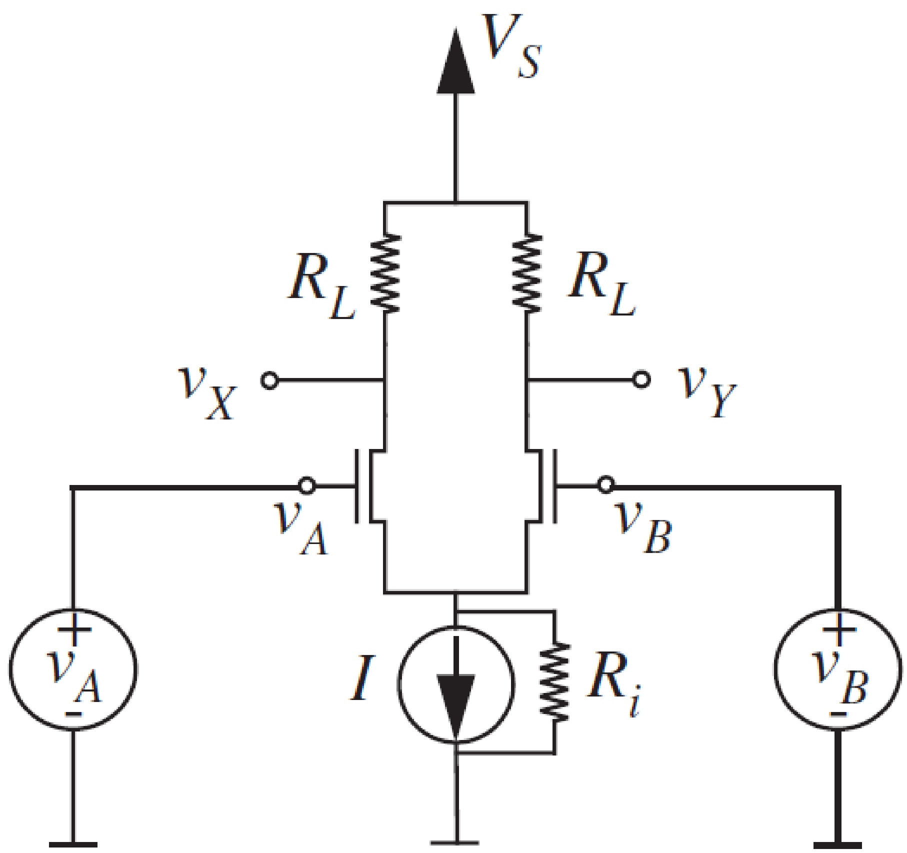
The output obtained was



Oscilloscope - NI ELVISmx
LabVIEW
Sample Rate: 25.00 kS/s
Timeout
CH0 Meas: RMS: 5.427 V Freq: 49.897 Hz Vp-p: 12.578 V
Basic Settings
Advanced Settings
Channel 0 Settings
Source
AI 2
Enabled
Probe
1x
Coupling
DC
Scale Volts/Div
Vertical Position (Div)
2 V
0
Channel 1 Settings
Source
AI 0
Enabled
Probe
1x
Coupling
DC
Scale Volts/Div
Vertical Position (Div)
500 mV
0
Timebase
Time/Div
10 ms
Trigger
Type
Immediate
Slope
Source
TRIG
Level (V)
0
Horizontal Position (%)
50
Instrument Control
Device
Dev3 (NI ELVIS II+)
Acquisition Mode
Run Continuously
Run
Stop
Print
Log
Help
Autoscale
Print
Cursors Settings
Cursors On
C1 CH 0
C2 CH 1
Display Measurements
CH 0
CH1
Graph Controls
Graph Properties

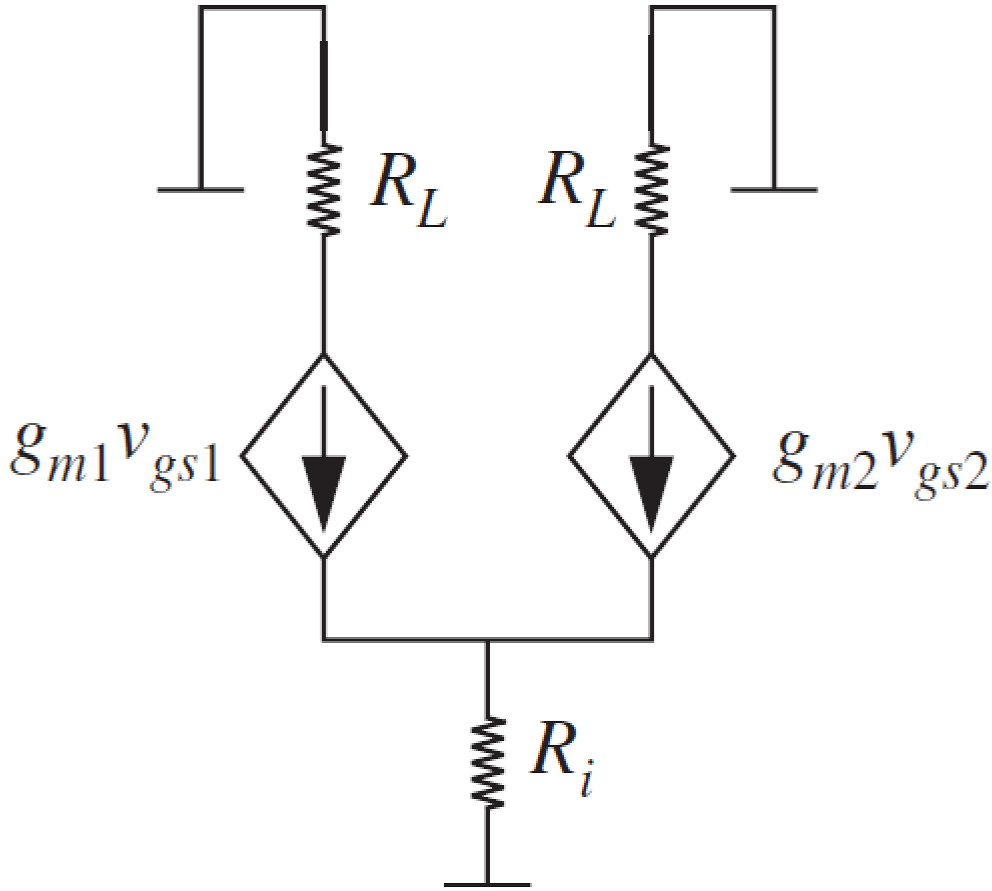
Discuss the following theoretical aspects:

a. **Small signal model of a difference amplifier (you can use a MOSFET or BJT based design)**



Source coupled differential amplifier

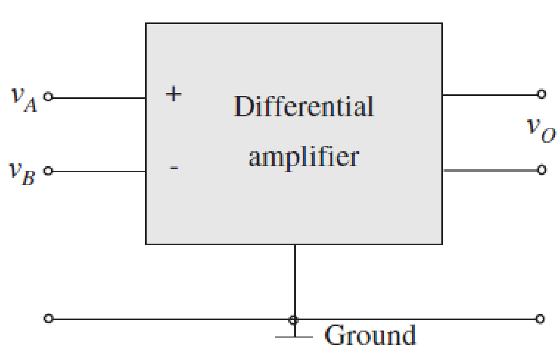
V_A and V_B are inputs, and V_X and V_Y are the output voltages. Also, v_a and v_b are small variations in inputs, and v_x and v_y correspond to small-signal output variations. The source-coupled pair is connected to the DC source(with current provided equally to I) in a series with high internal resistance, R_i.



Small-signal model of the differential amplifier

In the small-signal model, the current source with internal resistance R_i behaves as a resistance R_i. MOSFETs are replaced by their small equivalent current source. Voltages v_{gs1} and v_{gs2} are the small-signal voltages between the gate and source of the two input MOSFETs resulting from a small change in the input voltages v_A and v_B. The g_{m1} and g_{m2} are gain parameters for the MOSFETs that depend on the operating point values of current through them.

(i)Calculate the common mode and difference mode gain



Difference-mode component:

$V_D = V_A - V_B$

Common-mode component:

$$V_C = \frac{V_A + V_B}{2}$$

The output of the differential amplifier is

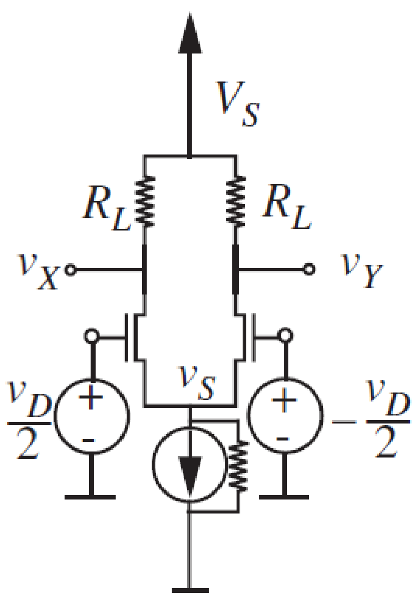
$$V_0 = A_D V_D + A_C V_C$$

From the difference-mode component and Common-mode component, we can write input as

$$V_A = V_C + \frac{V_D}{2}$$

$$V_B = V_C - \frac{V_D}{2}$$

Differential Mode Gain



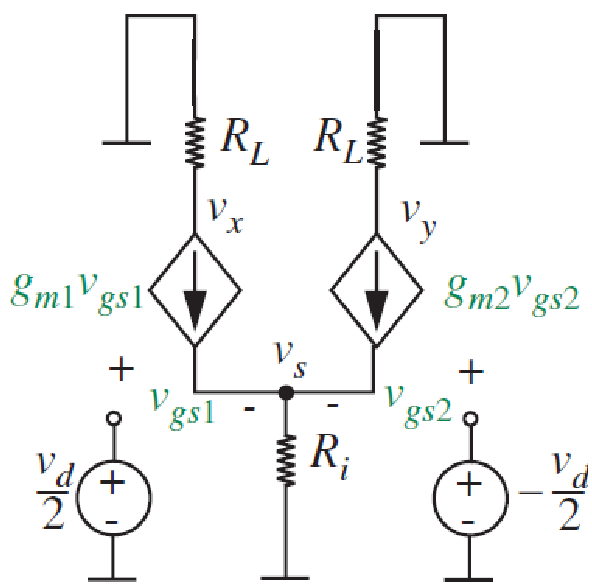


Fig1: differential mode input only
Fig2: a small-signal model for fig1 circuit

Assuming that the two MOSFET have identical characteristics

$$g_{m1} = g_{m2} = g_m$$

Now applying KCL at node V_S

$$g_m v_{gs1} + g_m v_{gs2} = v_s / R_i \qquad \ldots(1)$$

From the figure we get,

$$\frac{v_d}{2} - v_{gs1} = v_s$$

$$-\frac{v_d}{2} - v_{gs2} = v_s$$

Substituting v_{gs1} and v_{gs2} in terms of v_d and v_s in equation (1),

$$g_m\left(\frac{v_d}{2} - v_s\right) + g_m\left(-\frac{v_d}{2} - v_s\right) = \frac{v_s}{R_i}$$

$$-2g_m v_s = \frac{V_s}{R_i}$$

Since g_m and R_i are independent of each other, $v_s = 0$

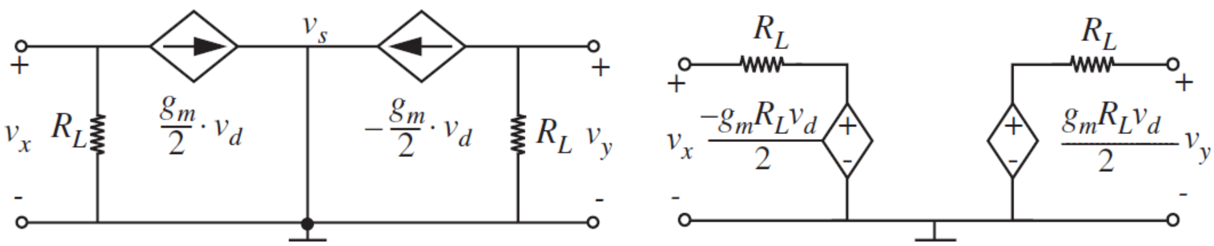


Fig 1: Differential mode simplified model
Fig 2: Difference-mode Thevenin equivalent model

From the Thevenin model, we see that,

$$v_x = -\frac{g_m R_L v_d}{2}$$

$$v_y = \frac{g_m R_L v_d}{2}$$

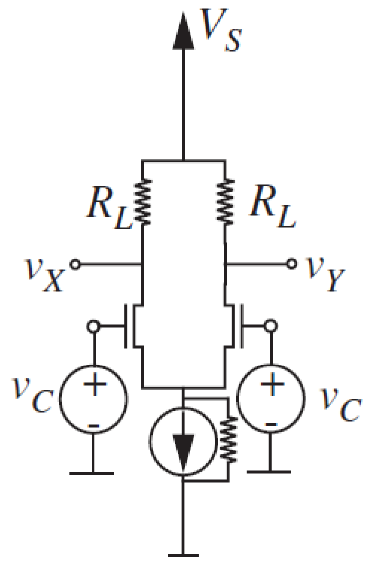
The small-signal output voltage across the output terminal pair is

$$v_o = v_x - v_y = -g_m R_L v_d$$

Thus, the difference-mode small-signal mode

$$A_d = \frac{v_0}{v_d} = -g_m R_L$$

Common mode Gain



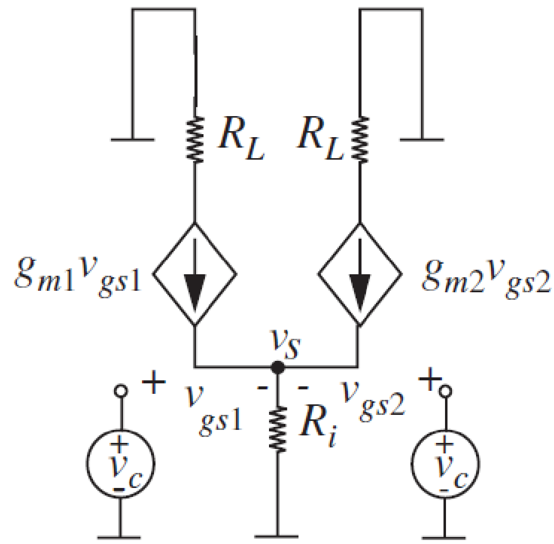


Fig 1: Common mode input only

Fig 2: Small-signal model

Common mode input denoted by v_c.

Here we can see that $v_{gs1} = v_{gs2} = v_{gs}$ and $v_{gs} = v_c - v_s$

Now applying KCL at v_s,

$$g_m v_{gs} + g_m v_{gs} = \frac{v_s}{R_i}$$

$$2g_m v_{gs} = \frac{v_c - v_{gs}}{R_i}$$

$$v_{gs} = \frac{1}{2g_m R_i + 1} v_c$$

Assuming R_i is too large, so $2g_mR_i >> 1$, we have

$$v_{gs} \approx \frac{1}{2g_m Ri} v_c$$

From the Thevenin circuit, we get,

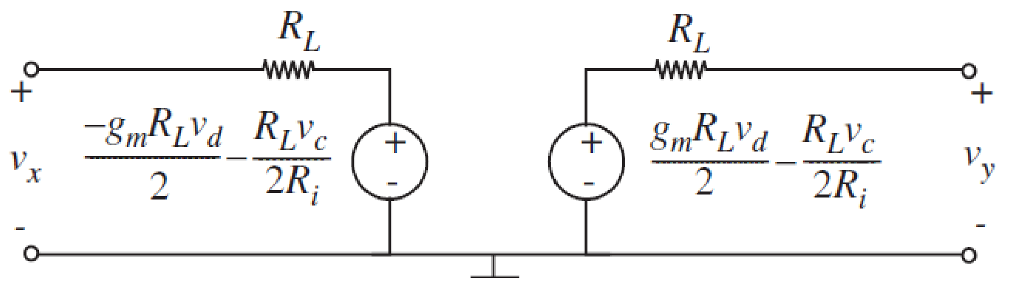
$$v_x = v_y = \frac{-R_L v_C}{2R_i}$$

$$v_o = v_X - v_Y = 0$$

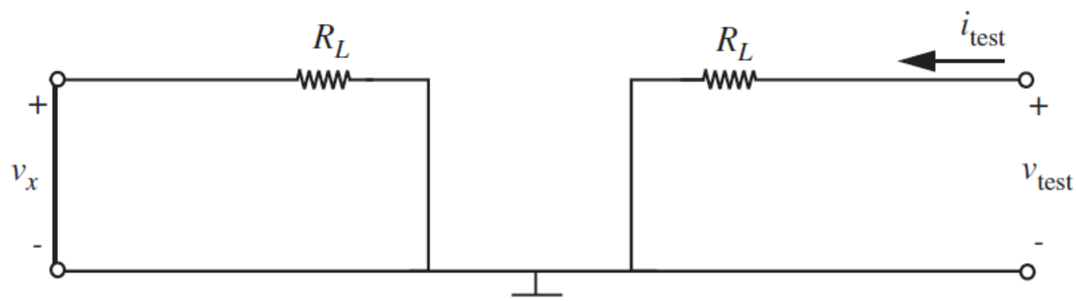
Thus, the common-mode small-signal gain is 0.

$A_C = 0$.

(ii) Using an appropriate equivalent (Thevenin or Norton), calculate the input and output resistances of the abovementioned circuit



Difference amplifier Thevenin equivalent circuit



Difference amplifier output resistance

For small input signals v_a and v_b, no current will flow into the MOSFETs. Thus, we have **infinite** input resistances.

For calculating small-signal output resistance, we turn off all independent sources by setting $v_a = 0$ and $v_b = 0$, in effect, turning off v_c and v_d. So, introduce a test voltage at the desired output and short the other output to ground.

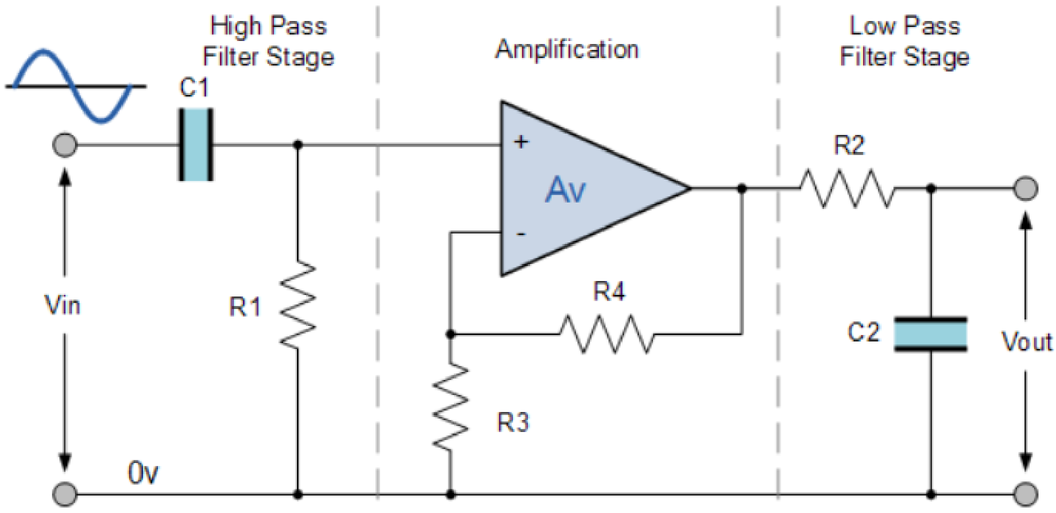
Thus, the output resistance looking into ports v_x or v_y and ground will be $\mathbf{R_L}$.

Input resistance: infinite

Output resistance: R_L

b. Active Band Pass RC Filter

(i) Derive the transfer function of the active RC filter using the node or relevant method



From voltage divider equation- v^{+} at the non-inverting input of op-amp can be given as

$$v^{+} = \frac{V_{in}R_1}{R_1 + \frac{1}{sC_1}} \qquad (s = jw)$$

Also, since the op-amp is being used as a non-inverting amplifier, the output voltage v_{out} will be-

$$v_{out} = \left(1 + \frac{R_4}{R_3}\right).v^{+}$$

$$\therefore v_{out} = \left(1 + \frac{R_4}{R_3}\right).\frac{V_{in}R_1}{R_1 + \frac{1}{sC_1}} \quad \text{substituting for } v^{+}$$

Again, using the voltage divider equation to find out V_{out}

$$V_{out} = \frac{v_{out}.\frac{1}{sC_2}}{R_2 + \frac{1}{sC_2}}$$

$$\therefore V_{out} = \left(1 + \frac{R_4}{R_3}\right).\frac{V_{in}R_1}{R_1 + \frac{1}{sC_1}}.\frac{\frac{1}{sC_2}}{R_2 + \frac{1}{sC_2}} \quad \text{substituting for } v_{out}$$

After multiplying the denominator and numerator by sC_1 and sC_2 and factoring the denominator-

$$V_{out} = \left(1 + \frac{R_4}{R_3}\right). \frac{sR_1C_1}{(sR_1C_1+1)(sR_2C_2+1)}. V_{in}$$

So, the transfer function of the active RC filter will be-

$$H(s) = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_4}{R_3}\right). \frac{sR_1C_1}{(sR_1C_1+1)(sR_2C_2+1)}$$

(ii) Use MATLAB or an equivalent tool to show the filter response and stability (Bode and pole-zero plot) using the transfer function derived above

(iii) Explain the plots in reference to the design specifications

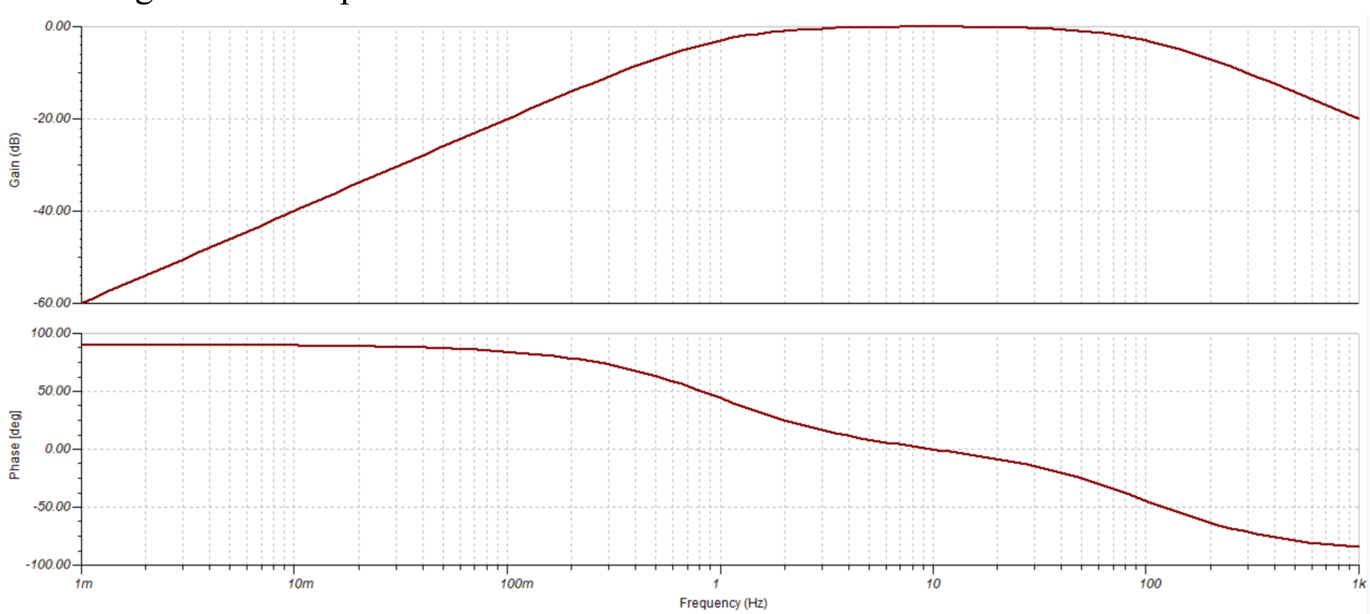
For the above transfer function, the poles and zeros are as follows-

Zeroes = 0

Poles = $\frac{-1}{R_2C_2}, \frac{-1}{R_1C_1}$

In the filter, we created the values $R_1C_1 = 0.16, R_2C_2 = 0.0016$ were taken

Following is the Bode plot of the above transfer function



In the filter designed above, we took $R_1 = 1.6\ k\Omega,\ C_1 = 100\mu F,\ R_2 = 1.6\ k\Omega\ and\ C_2 = 1\mu F$ so that the cut in the frequency of the High Pass filter stage would be-

$$f = \frac{1}{2\pi R_1C_1} = 1\ Hz$$

And the cut off frequency of the Low Pass Filter stage would be-

$$f = \frac{1}{2\pi R_2 C_2} = 100\ Hz$$

As seen in the above Bode-Plot, the pass band starts at 1 Hz and stops at 100 Hz, which was required. The pole-zero plot shows a second-order system; therefore, as per the design specifications, it also has a roll-off rate of >= 40 dB per decade.