Bangladesh University of
Engineering and Technology

Report on designing appropriate bio-signal measurement device for the ECoG signal

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Course Name: Biomedical Instrumentation and Measurements Sessional

Group No: 02

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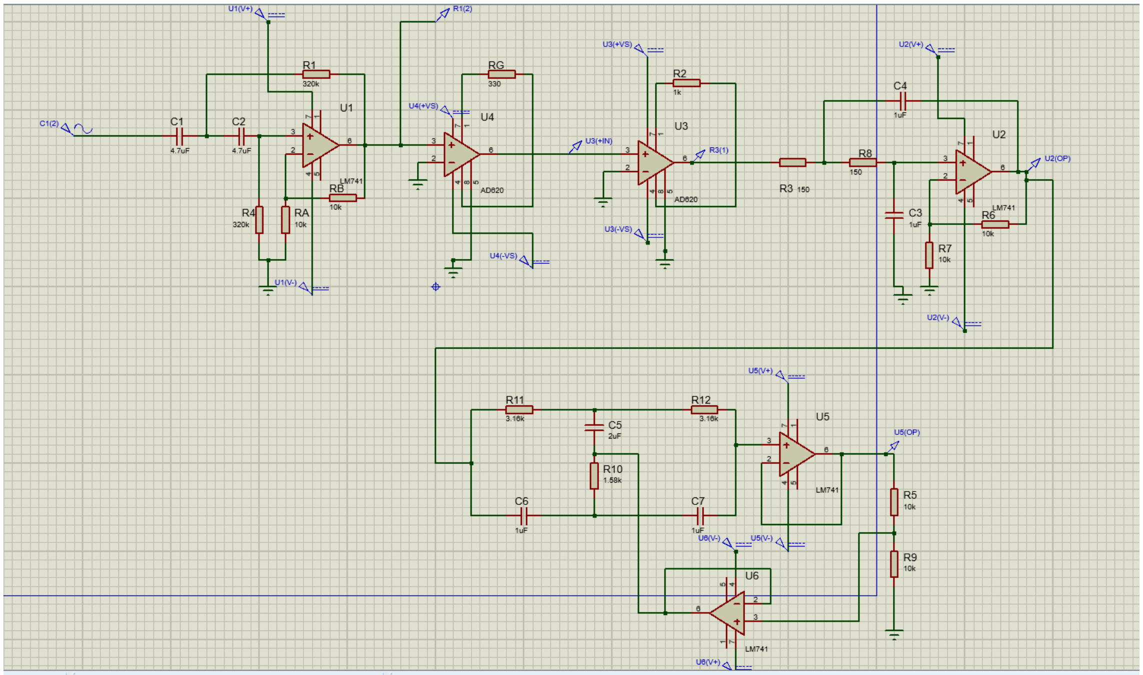
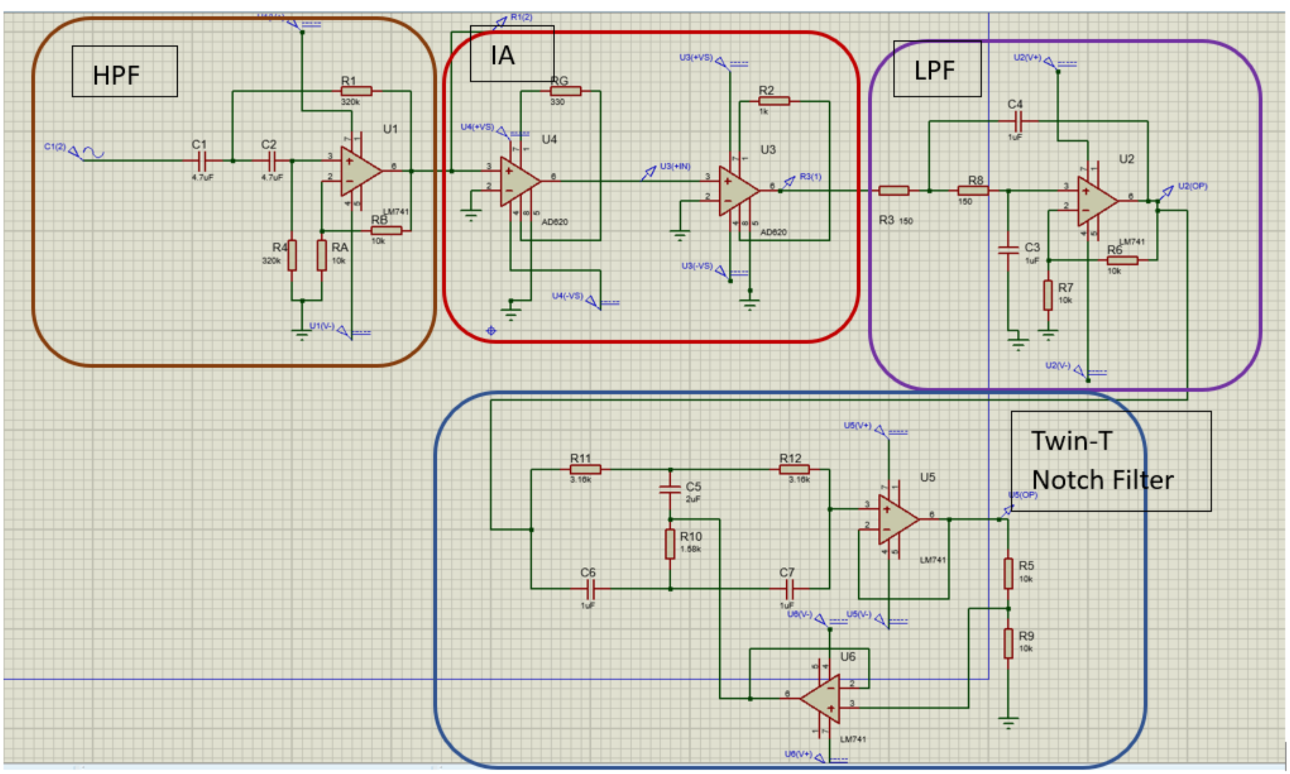
<u>Circuit Schematics:</u>

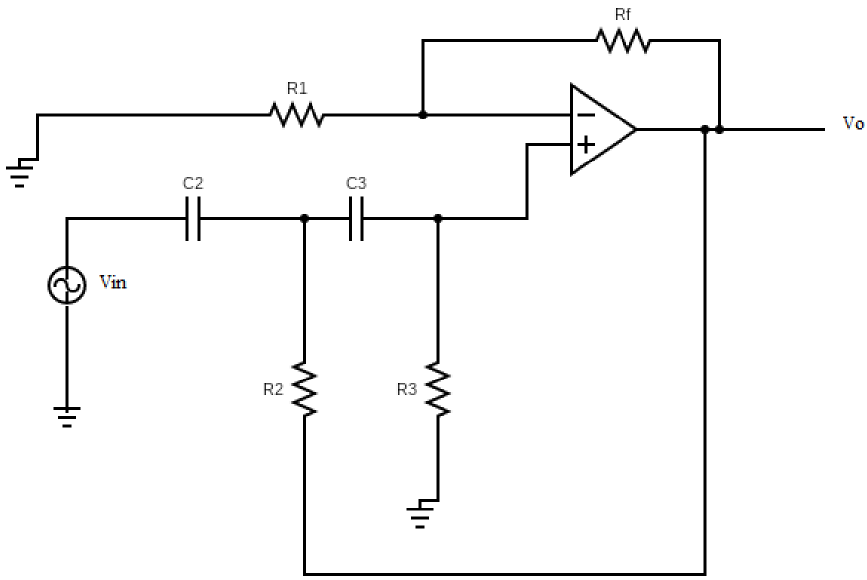
The following is the design of our circuit to make signal amplitude ranging between 0-5 V -

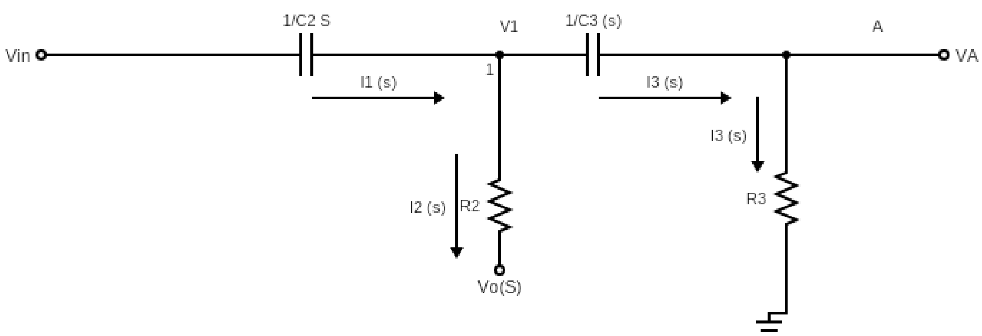




Gain and Cut off frequency derivation:

Second Order High Pass Filter:





Now applying KCL at Node 1, we get

$$I1\ (s) = I2\ (s) + I3\ (s)$$

$$or, \frac{Vin - V1}{\frac{1}{C2S}} = \frac{V1 - V0}{R2} + \frac{V1 - VA}{\frac{1}{C3S}}$$

$$or, (Vin - V1)C2S = \frac{V1 - V0}{R2} + (V1 - VA)C2S$$

$$or, V_A C_{3S} = \frac{V1 - V0}{R2} + V_1 C_{2S} + V_1 C_{2S} - V_{in} C_{2S}$$

$$or, V_A = \frac{V_1 \,(1 + R_2 C_{3S} + R_2 C_{2S}) - V_0 - V_{in} R_2 C_{2S}}{R_2 C_{3S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Applying KCL in node A,

$$I_3 = I_4$$

$$or, \frac{V_1 - V_A}{\frac{1}{C_{3S}}} = \frac{V_A - 0}{R_3}$$

$$or, V_1 C_{3s} = \frac{V_A}{R_3} + V_A C_{3S}$$

$$or, V_1 = V_A \frac{1 + R_3 C_{3S}}{R_3 C_{3S}}$$

Putting the value of V_1 in equation (1),

$$V_A = \frac{\left[\frac{V_A (1 + R_3 C_{3S})}{R_3 C_{3S}}\right](1 + R_2 C_{3S} + R_2 C_{2S}) - V_0 - V_{in} C_2 R_{2S}}{R_2 C_{3S}}$$

$$or, V_A R_2 C_{3S} - \frac{V_A (1 + R_3 C_{3S})}{R_3 C_{3S}}(1 + R_2 C_{3S} + R_2 C_{2S}) = -V_0 - V_{in} C_2 R_{2S}$$

$$or, V_A \frac{R_2R_3C_3^2S^2 - 1 - R_2C_3S - R_2C_2S - R_3C_3S - R_2R_3C_3^2S^2 - R_2R_3C_2C_3S^2}{R_3C_3S}$$
$$= -V_0 - V_{in}C_2R_2S$$

$$or, -V_A\left[\frac{R_2R_3C_2C_3S^2 + S(R_2C_2 + R_2C_3 + R_3C_3) + 1}{R_3C_2S}\right] = -V_0 - V_{in}C_2R_2S$$

$$or, V_A = \frac{(V_0 + V_{in}SR_2C_2)R_3C_3S}{R_2R_3C_2C_3S^2 + S(R_2C_2 + R_2C_3 + R_3C_3) + 1}$$

Now, $V_0 = A_FV_A$ $[where\ A_F = 1 + \frac{Rf}{R1}]$

$$or, V_0 = A_F[\frac{(V_0 + V_{in}SR_2C_2)R_3C_3S}{R_2R_3C_2C_3S^2 + S(R_2C_2 + R_2C_3 + R_3C_3) + 1}]$$

$$or, (V_{in}SR_2C_2)R_3C_3S = -R_3C_3SV_0A_F + V_0[R_2R_3C_2C_3S^2 + S(R_2C_2 + R_2C_3 + R_3C_3) + 1]$$

$$or, \frac{V_0}{V_{in}} = \frac{R_2C_2R_3C_3S^2A_F}{R_2R_3C_2C_3S^2 + S(R_2C_2 + R_2C_3 + R_3C_3 - R_3C_3A_F) + 1)}$$

$$= \frac{S^2A_F}{S^2 + S\,\frac{R_2C_2 + R_2C_3 + R_3C_3 - R_3C_3A_F}{R_2C_2R_3C_3} + \frac{1}{R_2C_2R_3C_3}}$$

Now, comparing with the standard equation,

$$\frac{V_0}{V_{in}} = \frac{A}{S^2 + \alpha w_nS + w_n^2}$$

$$\alpha = \frac{R_2C_2 + R_2C_3 + R_3C_3\,(1 - A_F)}{\sqrt{R_2C_2R_3C_3}}$$

$$w_n = \frac{1}{\sqrt{R_2C_2R_3C_3}} \; or, 2\pi f_c = \frac{1}{\sqrt{R_2C_2R_3C_3}}$$

$$or, f_c = \frac{1}{2\pi\sqrt{R_2C_2R_3C_3}}$$

Where lower cut off frequency is f_c

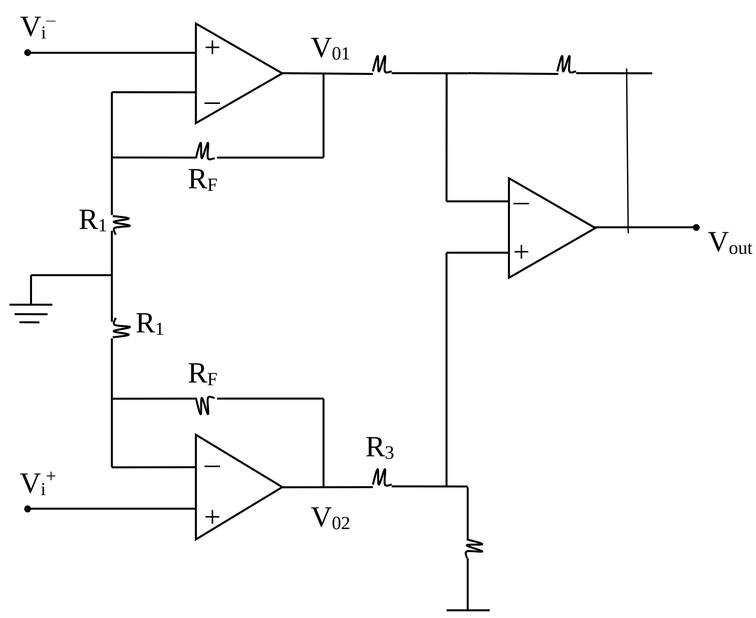
So, from equation we get,

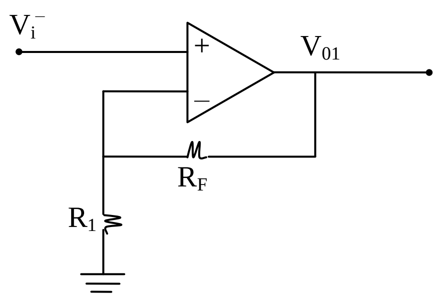
$$A_F = 1 + \frac{Rf}{R1} = \frac{V_0}{V_A}$$

And cut off frequency, $\boldsymbol{f_c = \frac{1}{2\pi\sqrt{R_2C_2R_3C_3}}}$

Gain, **G = 20log($\boldsymbol{A_F}$) = 20log** $\left(\mathbf{1} + \boldsymbol{\frac{Rf}{R1}}\right)$

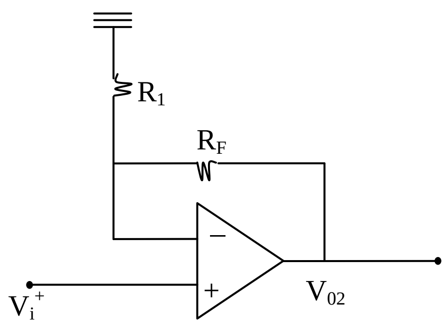
INA 128:





non inventing op amp

$$V_{01} = \left(1 - \frac{R_F}{R_1}\right) V_i^-$$



$$V_{02} = \left(1 - \frac{R_F}{R_1}\right) V_i^+$$

$$V_0 = V_{02} - V_{01} = \left(1 + \frac{R_F}{R_1}\right) \Delta V_i \quad [AV_i = V_i^+ - V_i^-]$$

If V_{01} on, V_{O2} off –

$$V' = \frac{R_4}{R_3} V_{O1}$$

V_{02} on, V_{01} off-

$$V_A = \frac{R_4}{R_4+R_3} V_{O2}$$

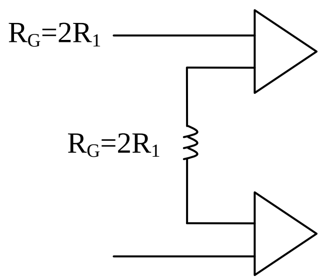
$$\therefore V'' = \frac{R_4}{R_4+R_3} V_{O2} \left(1 + \frac{R_4}{R_3}\right)$$

$$= \frac{R_4}{R_4+R_3} V_{O2} \frac{R_3+R_4}{R_3}$$

$= \frac{R_4}{R_3} V_{O2}$

$V_{Out} = \frac{R_4}{R_3}(V_{O2} - V_{O1})$

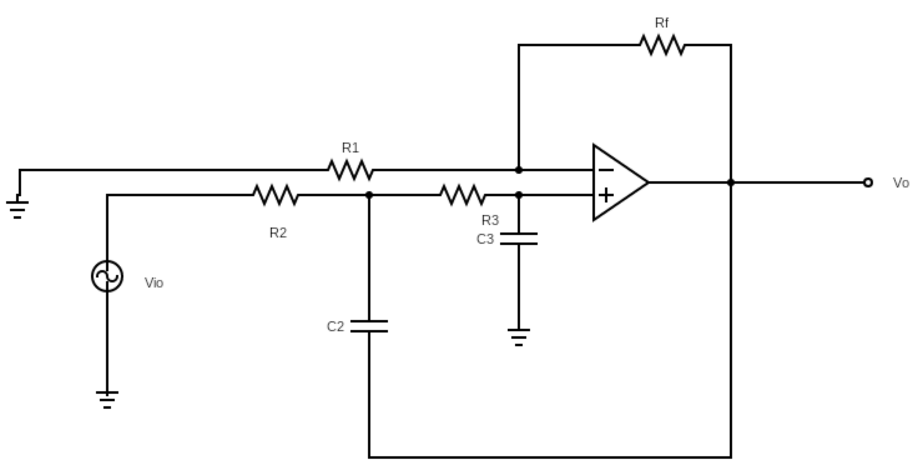
$$\boxed{V_{out} = \frac{R_4}{R_3}\left(1 + \frac{R_F}{R_1}\right) \ \Delta V_i}$$



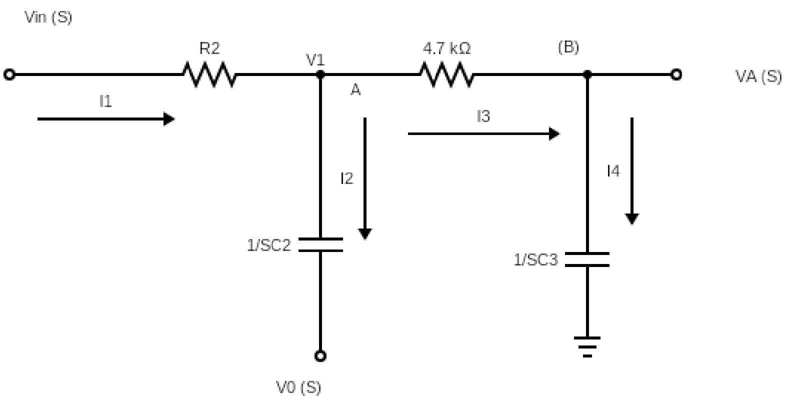
$$G = \frac{R_4}{R_3}\left(1 + \frac{R_F}{R_1}\right)$$

If $R_4 = R_3, G = 1 + \frac{2R_F}{R_G}$

2nd order low pass filter:



Transfer function:



KCl at node A,

$I_1 = I_2 + I_3$

or, $\frac{V_{in}(s)-V_1(s)}{R_2} = \frac{V_1(s)-V_0(s)}{1/sC_2} + \frac{V_1(s)-V_A(s)}{R_3}$

or, $\frac{V_{in}-V_1}{R_2} = (V_1 - V_0)SC_2 + \frac{(V_1-V_A)}{R_3}$

or, $\frac{V_{in}-V_1}{R_2} = (V_1 - V_0)SC_2 + \frac{V_1}{R_3} - \frac{V_A}{R_3}$

or, $\frac{V_A}{R_3} = (V_1 - V_0)SC_2 + \frac{V_1}{R_3} - \left(\frac{V_{in}-V_1}{R_2}\right)$

or, $\frac{V_A}{R_3} = \frac{V_1SC_2R_2R_3 - V_0SC_2R_2R_3 + V_1R_2 - V_{in}R_3 + V_1R_3}{R_2R_3}$

or, $V_A = \frac{V_1(SC_2R_2R_3+R_2+R_3) - V_0SC_2R_2R_3 - V_{in}R_3}{R_2}$ ....(1)

KCl at node B:

$I_3 = I_4$

or, $\frac{V_1-V_A}{R_3} = \frac{V_A-0}{1/SC_3}$

or, $\frac{V_1}{R_3} = \frac{V_A}{R_3} + V_A.SC_3$

or, $\frac{V_1}{R_3} = V_A\left(\frac{1+SR_3C_3}{R_3}\right)$

or, $V_A = \frac{V_1}{1+SR_3C_3}$ ....(2)

Replacing $V_1 = V_A(1 + SR_3C_3)$ from (2) in (1):

$$V_A = \frac{V_A(1+SR_3C_3)(SC_2R_2R_3+R_2+R_3)-V_0SC_2R_2R_3-V_{in}R_3}{R_2}$$

or, $R_2V_A - V_A(1 + SR_3C_3)(SC_2R_2R_3 + R_2 + R_3) = -V_0SC_2R_2R_3 - V_{in}R_3$

or,$V_A[R_2 - SC_2R_2R_3 - R_2 - R_3 - S^2R_2R_3^2C_2C_3 - SR_2C_3R_3 - SR_3^2C_3] =$
$-V_0SC_2R_2R_3 - V_{in}R_3$

or, $V_A(SC_2R_2 + 1 + S^2R_2R_3C_2C_3 + SR_2C_3 + SR_3C_3) = V_0SC_2R_2 + V_{in}$

or, $V_A = \frac{V_0SC_2R_2+V_{in}}{[S^2R_2R_3C_2C_3+S(R_2C_2+R_3C_3+R_2C_3)+1]}$

Now, from the circuit-

$V_0 = \left(1 + \frac{R_F}{R_1}\right)V_A = A_FV_A$

Replacing V_A,

$$V_0 = A_F\left[\frac{V_0SC_2R_2+V_{in}}{S^2R_2R_3C_2C_3+S(R_2C_2+R_3C_3+R_2C_3)+1}\right]$$

$V_0 = [S^2R_2R_3C_2C_3 + S(R_2C_2 + R_3C_3 + R_2C_3) + 1 - A_FSR_2C_2] = A_F.V_{in}$

$$\frac{V_0}{V_{in}} = \frac{A_F}{S^2R_2R_3C_2C_3+S(R_2C_2+R_3C_3+R_2C_3-A_FR_2C_2)+1}$$

Here is the transfer function.

Again, from standard LPF Transfer function,

$$\frac{V_0}{V_{in}} = \frac{A_F}{S^2+\alpha W_a S+W_n^2}$$

$$\frac{V_0}{V_{in}} = \frac{A_F/R_2R_3C_2C_3}{S^2+S\left[\frac{R_2C_2+R_3C_3+R_2C_3-A_FR_2C_2}{R_2R_3C_2C_3}\right]+\frac{1}{R_2R_3C_2C_3}}$$

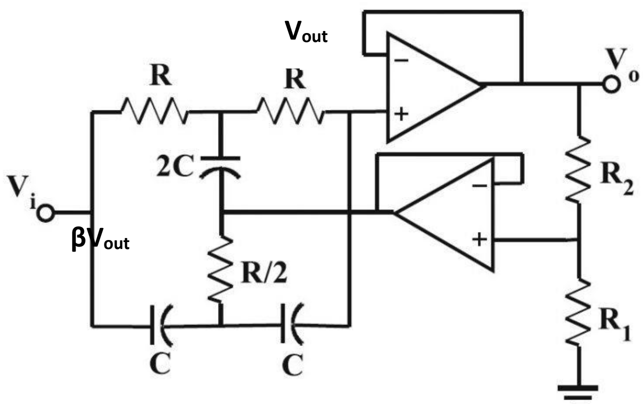
So, $W_n^2 = \frac{1}{R_2R_3C_2C_3}$

$$W_n = \frac{1}{\sqrt{R_2R_3C_2C_3}}$$

or, $\mathbf{f_c} = \frac{\mathbf{1}}{\mathbf{2\pi\sqrt{R_2R_3C_2C_3}}}$

Gain, **G = 20log(** $\boldsymbol{A_F}$**)** $= \mathbf{20log}\ (\mathbf{1} + \frac{\boldsymbol{Rf}}{\boldsymbol{R1}})$

2nd order Notch filter:



Here, $\beta = \frac{R_1}{R_1+R_2}$

Applying KCL at node A,

$$\frac{V_A-V_{in}}{R} + \frac{V_A-V_{out}}{R} + \frac{V_A-\beta V_{out}}{1/2sC} = 0$$

$$\Rightarrow V_A\left(\frac{2}{R}+2sC\right)=\frac{V_{in}+V_{out}}{R}+\frac{\beta V_{out}}{1/2sC}$$

$$\Rightarrow V_A=\frac{V_{in}+V_{out}(1+2\beta sRC)}{2(1+sRC)} \text{ ....(i)}$$

Applying KCl at node B,

$$\frac{V_B-\beta V_{out}}{R/2}+\frac{V_B-V_{in}}{1/sC}+\frac{V_B-V_{out}}{1/sC}=0$$

$$\Rightarrow V_B\left(\frac{2}{R}+2sC\right)=(V_{in}+V_{out})sC+\frac{\beta V_{out}}{R/2}$$

$$\Rightarrow V_B=\frac{(V_{in}+V_{out})sRC+2\beta V_{out}}{2(1+sRC)} \text{ ......(ii)}$$

Applying KCl at node P,

$$\frac{V_{out}-V_A}{R}+\frac{V_{out}-V_B}{1/sC}=0$$

$$V_{out}\left(\frac{1}{R}+sC\right)=\frac{V_A}{R}+sCV_B$$

$$V_{out}=\frac{V_A+sRC\,V_B}{1+sRC} \text{ ....(iii)}$$

Substituting (i) and (ii) into (iii), we get,

$$V_{out}=\frac{V_{in}+V_{out}(1+2\beta sRC)+(V_{in}+V_{out})s^2R^2C^2+2sRC\beta V_{out}}{2(1+sRC)^2}$$

$$\Rightarrow 2V_{out}(1+sRC)^2=V_{in}(1+s^2R^2C^2)+V_{out}(1+s^2R^2C^2+4sRC\beta)$$

$$\Rightarrow V_{out}(2+4sRC+2s^2R^2C^2-1-s^2R^2C^2-4sRC\beta)=V_{in}(1+s^2R^2C^2)$$

$$\Rightarrow \frac{V_{out}}{V_{in}}=\frac{1+s^2R^2C^2}{s^2R^2C^2+4sRC(1-\beta)+1}$$

$$\therefore H(s)=\frac{s^2+\frac{1}{R^2C^2}}{s^2+\frac{4s(1-\beta)}{RC}+\frac{1}{R^2C^2}}$$

where $w_n^2 = \frac{1}{R^2C^2}$

$\Rightarrow w_n = \frac{1}{RC}$

$\Rightarrow \mathbf{f_n = \frac{1}{2\pi RC}}$

Theoretical Calculation:

For High pass filter:

$$R_2 = R_3 = 320\ k\Omega,\ C_2 = C_3 = 4.7\mu F,\ R_1 = R_F = 10\ k\Omega$$

$$f_c = \frac{1}{2\pi\sqrt{R_2C_2R_3C_3}} = 0.01\ Hz$$

$\frac{V_0}{V_{in}} = 1 + \frac{R_F}{R1} = 1 + \frac{10k}{10k} = 2$

And gain, 20log $(1 + \frac{Rf}{R1})$ = 6.02 dB

For INA 128: We used 2 INA 128 to obtain optimum gain.

For 1st INA,

R_F = 25 Kohm, R_G = 330 ohm

$$G = 1 + \frac{2R_F}{R_G}$$

G= 152.5

For 2nd INA,

R_F = 25 Kohm, R_G = 1 Kohm

G= 51

So, total gain = 152.5× 51 = 7777.5

For Low pass filter:

$$\mathrm{R_2 = R_3 = 150\Omega}$$
$$\mathrm{C_2 = C_3 = 1\mu F}$$

$$\mathrm{f_c = \frac{1}{2\pi\sqrt{(150)^2 \times (10^{-6})^2}} = 1061.03\ Hz}$$

$$\frac{\mathrm{V_0}}{\mathrm{V_{in}}} = 1 + \frac{\mathrm{R_F}}{\mathrm{R}} = 1 + \frac{10\mathrm{k}}{10\mathrm{k}} = 2$$

$$\text{Gain, } \mathrm{G} = 20 \log\left(\frac{\mathrm{V_0}}{\mathrm{V_{in}}}\right) = 20 \log(2) = 6.02 \text{ dB}$$

For Notch filter:

$$\mathrm{R = 3.3k\Omega, C = 1\mu F}$$

$$\mathrm{f_n = \frac{1}{2\times\pi\times3.3\times10^{3}\times1\times10^{-6}} = 48.23\ Hz}$$

So, notch frequency is 48.23 Hz.

Total Gain:

$$\frac{\mathrm{V_0}}{\mathrm{V_{in}}} = 2\times 7777.5 \times 2 = 31110$$

As $\mathrm{V_{in}} = 0.1\ mV,\ \mathrm{V_0} = 3.111V$

Hence, The signal amplitude is in the required range.

Frequency response plot:

Practically observed:

As we need 10,000 gain for making the signal amplitude between 0-5V, this is hard to implement. Thereby we gained the signal by 10.

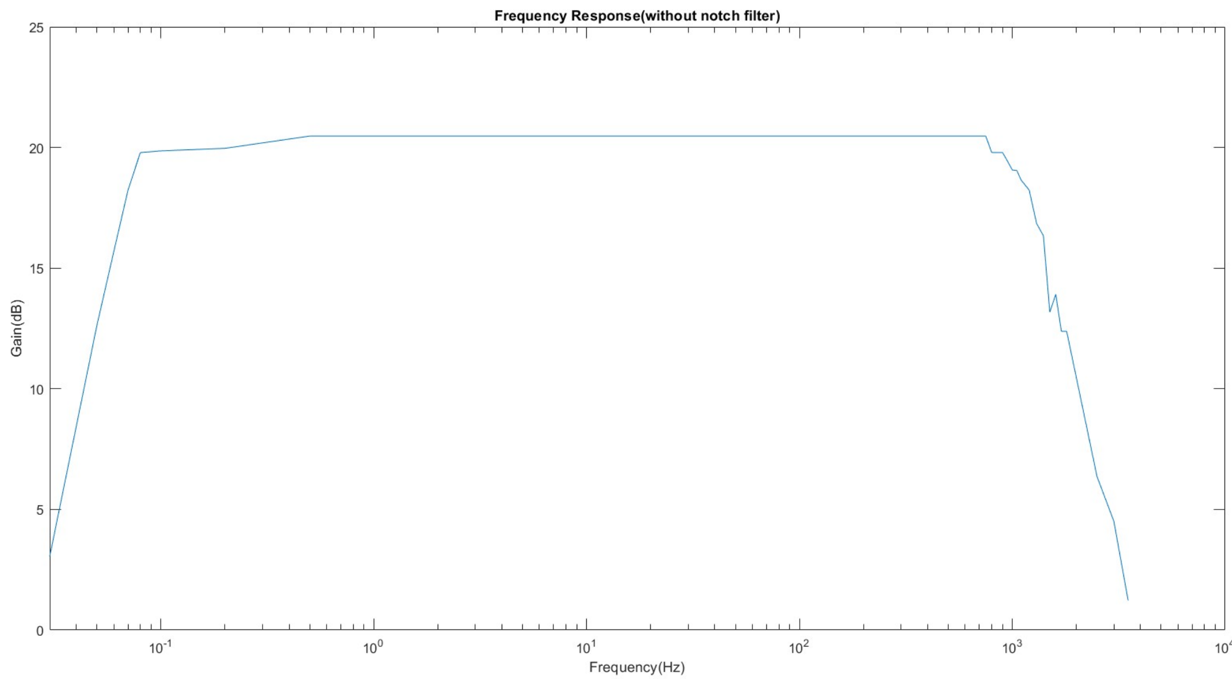
For Bandpass (without notch):

Vin= 0.5 V

Frequency	Gain(bandpass)	bandpass(V_out)
0.03	3.045766888	0.71
0.05	12.62887538	2.14
0.06	15.67807159	3.04
0.07	18.23380318	4.08
0.08	19.78899635	4.88
0.09	19.82452151	4.9
0.1	19.85990197	4.92
0.2	19.96518677	4.98
0.5	20.47327836	5.28
2	20.47327836	5.28
5	20.47327836	5.28
7	20.47327836	5.28
10	20.47327836	5.28
20	20.47327836	5.28
25	20.47327836	5.28
30	20.47327836	5.28
35	20.47327836	5.28

40	20.47327836	5.28
42	20.47327836	5.28
45	20.47327836	5.28
48	20.47327836	5.28
50	20.47327836	5.28
52	20.47327836	5.28
55	20.47327836	5.28
58	20.47327836	5.28
60	20.47327836	5.28
65	20.47327836	5.28
70	20.47327836	5.28
75	20.47327836	5.28
80	20.47327836	5.28
85	20.47327836	5.28
90	20.47327836	5.28
100	20.47327836	5.28
120	20.47327836	5.28
150	20.47327836	5.28
200	20.47327836	5.28
250	20.47327836	5.28
300	20.47327836	5.28
350	20.47327836	5.28
400	20.47327836	5.28
450	20.47327836	5.28

500	20.47327836	5.28
550	20.47327836	5.28
600	20.47327836	5.28
650	20.47327836	5.28
700	20.47327836	5.28
750	20.47327836	5.28
800	19.78899635	4.88
900	19.78899635	4.88
950	19.42551697	4.68
1000	19.06552673	4.49
1050	19.04616019	4.48
1100	18.64947529	4.28
1200	18.23380318	4.08
1300	16.85218479	3.48
1400	16.33807679	3.28
1500	13.17929685	2.28
1600	13.90963353	2.48
1700	12.38186661	2.08
1800	12.38186661	2.08
2500	6.361266699	1.04
3000	4.506185635	0.84
3500	1.229049582	0.576



<u>For Bandpass (with notch filter):</u>

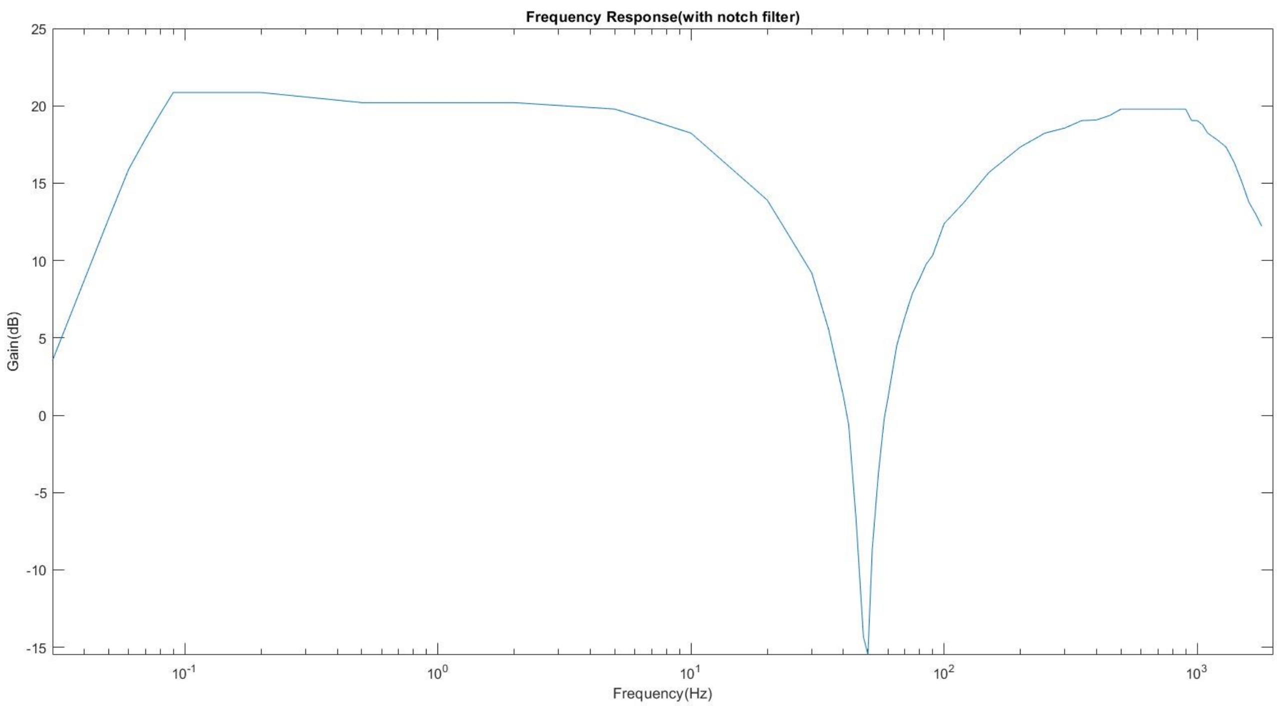
Vin= 0.5 V

Frequency	V_output(new)	Gain()
0.03	0.752	3.544957
0.05	2.16	12.70967
0.06	3.12	15.90369
0.07	3.92	17.88632
0.08	4.72	19.49944
0.09	5.52	20.85938
0.1	5.52	20.85938
0.2	5.52	20.85938

0.5	5.12	20.206
2	5.12	20.206
5	4.88	19.789
7	4.48	19.04616
10	4.08	18.2338
20	2.48	13.90963
25	1.84	11.31696
30	1.44	9.18785
35	0.944	5.52004
40	0.576	1.22905
42	0.464	-0.64904
45	0.224	-6.97444
48	0.096	-14.334
50	0.084	-15.4938
52	0.184	-8.68304
55	0.324	-3.7685
58	0.488	-0.211
60	0.568	1.107567
65	0.84	4.506186
70	1.04	6.361267
75	1.24	7.889034
80	1.38	8.818182
85	1.54	9.771014
90	1.64	10.31748

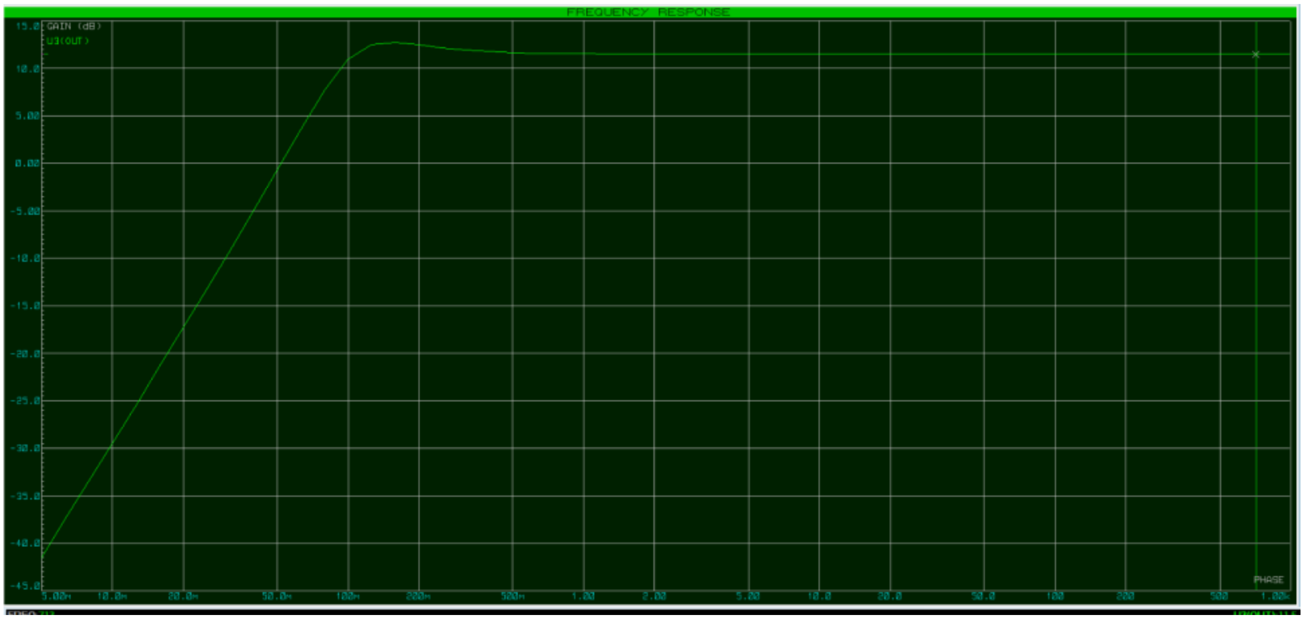
100	2.08	12.38187
120	2.44	13.7684
150	3.04	15.67807
200	3.68	17.33756
250	4.08	18.2338
300	4.24	18.56792
350	4.48	19.04616
400	4.5	19.08485
450	4.65	19.36966
500	4.88	19.789
550	4.88	19.789
600	4.88	19.789
650	4.88	19.789
700	4.88	19.789
750	4.88	19.789
800	4.88	19.789
900	4.88	19.789
950	4.48	19.04616
1000	4.48	19.04616
1050	4.34	18.77039
1100	4.08	18.2338
1200	3.88	17.79723
1300	3.68	17.33756
1400	3.28	16.33808

1500	2.84	15.08697
1600	2.44	13.7684
1700	2.24	13.02556
1800	2.04	12.2132



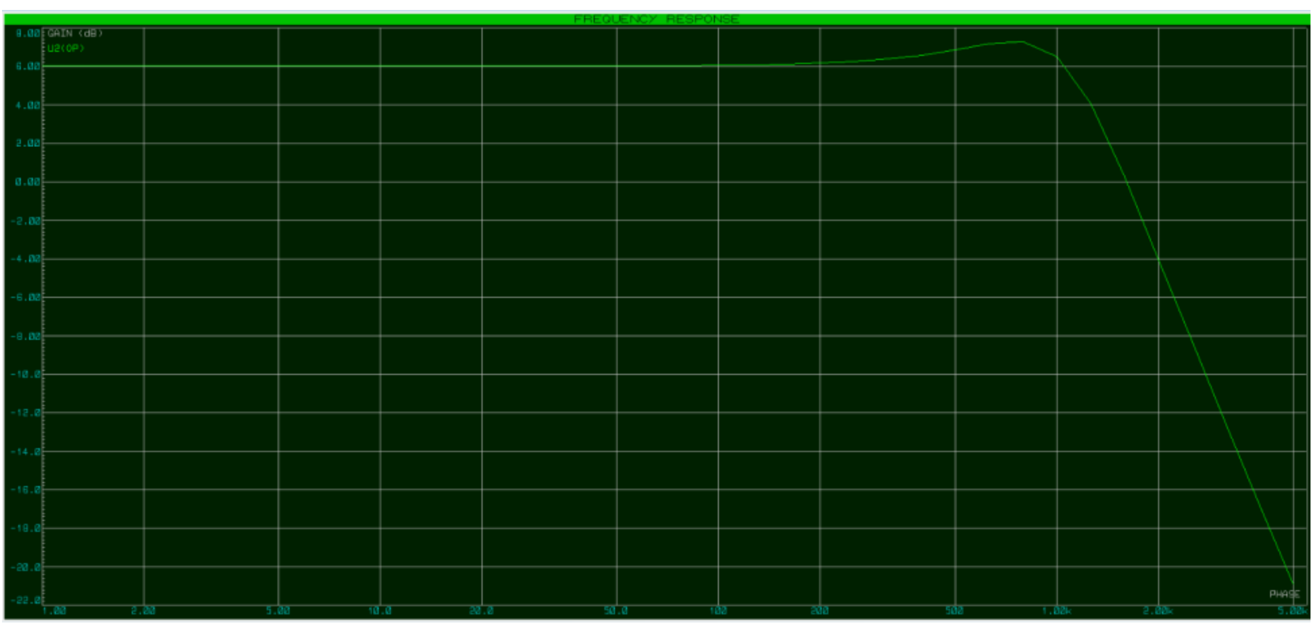
Proteus simulation:

- For High Pass Filter, obtained Frequency Response Graph is-



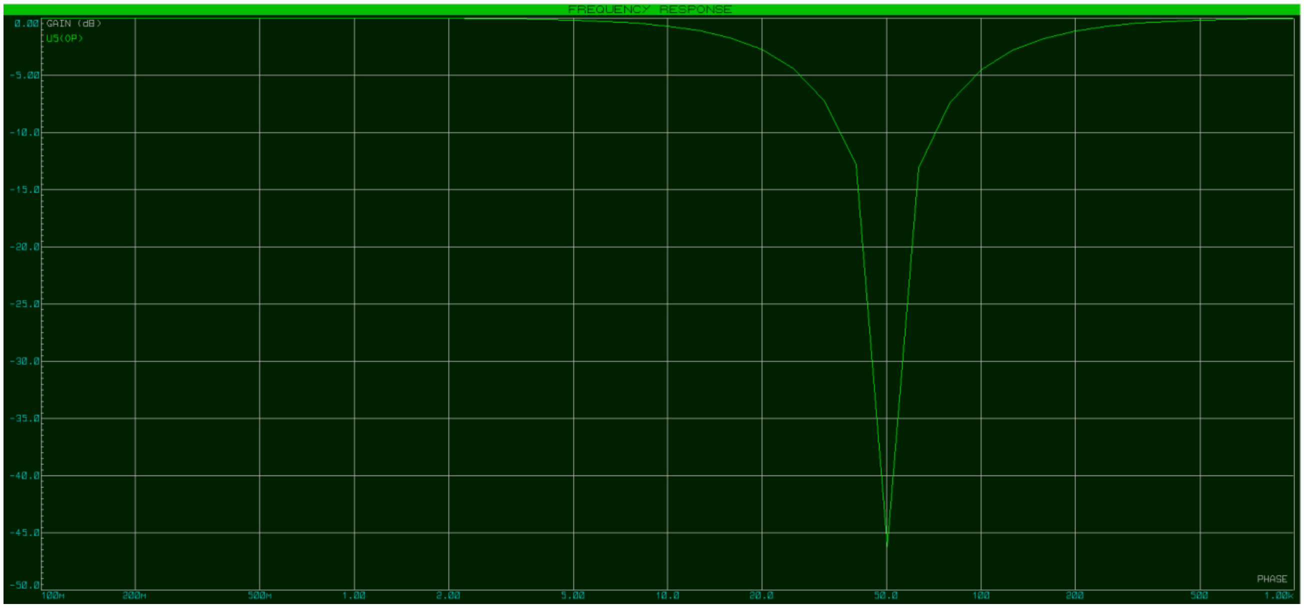
The observed lower cut-off frequency is 0.1V here.

- For Low pass filter, the frequency graph is-



Here the higher cut-off frequency is observed 1000 Hz, as expected.

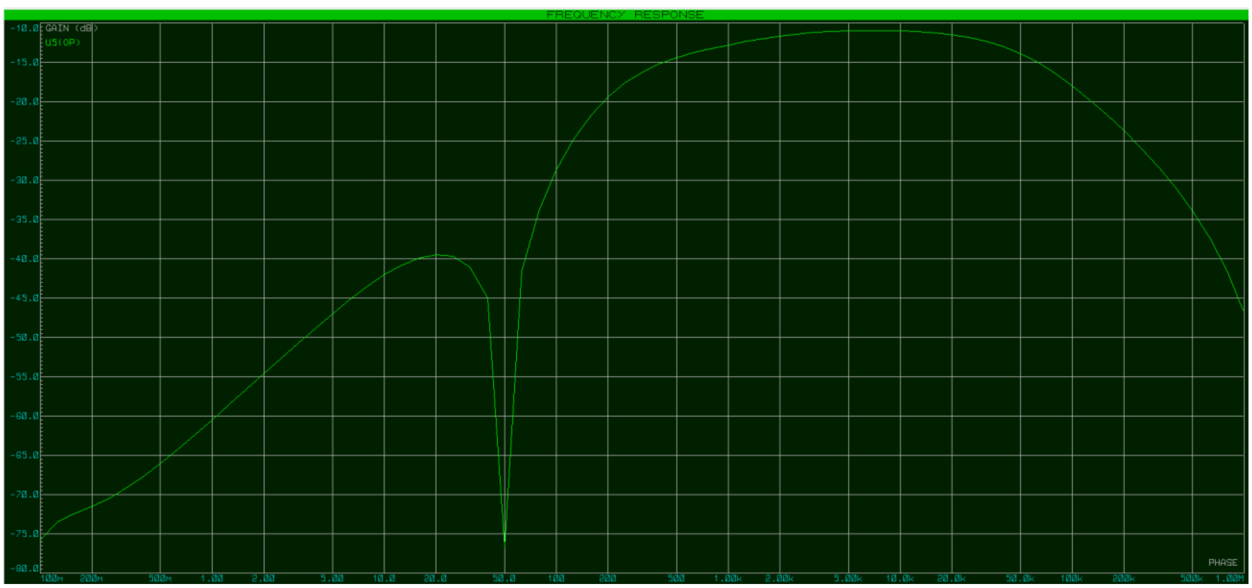
For Notch filter:



We have designed 2nd order T-twin notch filter. It is showing comparatively sharp elimination of power line noise gain at 50Hz, as calculated.

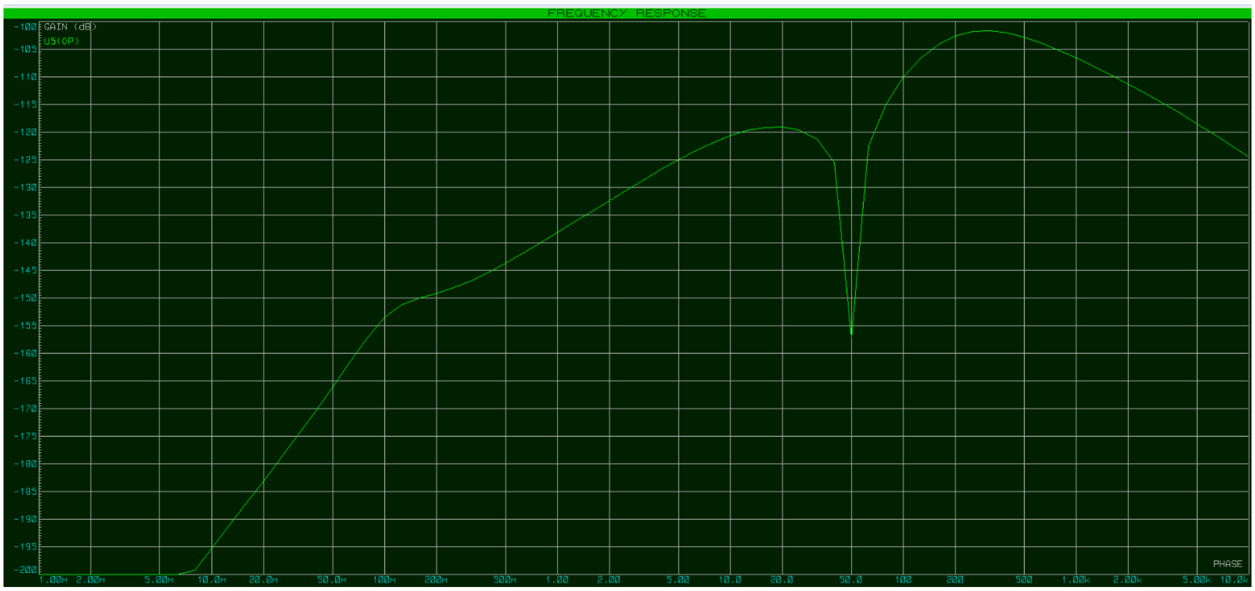
- Overall Frequency response after introducing Notch filter and Instrumentational amplifier according to the circuit_

The input voltage is 0.1mV (Vpp).



Discussion:

The cut off frequencies are quite distorted in the proteus simulation. Although the filters are individually working fine but altogether it finds difficulties in proper cascading. Specially, the calculated higher cut-off frequency was 1000Hz, we observed a very decrease in gain of the frequency band. But we got better result using additional 1st order LPF before the given 2nd order LPF and also increasing the input voltage up to 100mV.



Thus, several iterations made us believe that proteus might face difficulties in calculating at lower range. And also, with the increasing order of the filter, we could obtain sharp and targeted result in cut-off frequency. But in question of feasibility of practical implementation, we have limited our circuit up to 2nd order filters.

Though INA 128 can give gain upto 1000, it was not working properly when we wanted that level of huge gain. So, we cascaded 2 INA to obtain a gain of 7777.5.

However, our circuit is working fine practically. Thus, it proves that the calculation is right. But it was hard to implement 10,000 gain and oscilloscope do not take input of 0.1 mV. Therefore, we implement a circuit to obtain 10 gain with input 0.5V. It worked as expected. There were some noise observed in the circuit due to environmental interference.

We used a notch filter to remove 50Hz powerline noise. However, it attenuated some of the signal of ECoG in the near that frequency.