Indian Institute of Technology Bombay

Analog Circuits Lab
EE 230

Lab 11 - Electrocardiogram Simulation
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1 2nd-Order Low-Pass Filter

1.1 Aim

Design and simulate a 2nd-order low-pass ECG amplifier stage that:

1. Provides a DC gain of approximately 28dB
2. Exhibits a 3dB cutoff frequency of 150Hz
3. Uses ideal op-amp assumptions for analytical transfer functions

1.2 Design

1. **Topology:** Two cascaded inverting stages.
2. **Transfer Function:**
$$\frac{V_c}{V_{in}} = -A \times \frac{1}{1 + s\tau_1} \times \frac{1}{1 + s\tau_2} \tag{1}$$
with DC gain A and time constants $\tau_1 = R_7 C_2,\ \tau_2 = R_8 C_3$.
3. **Component Selection:**
   - Adjust resistor ratio to set gain: $A = 10^{(28dB/20)} \approx 25$; so $R_7/R_6 \approx 25$ which gives us $R_7 = 472.256\text{k}\Omega$
   - And 3dB frequency = 150Hz gives us $R_8 = 361.075\text{k}$
4. **Simulation Steps:**
   - **AC Sweep (1Hz–10kHz, decade):** Plot magnitude of V_c; extract DC gain and f_{3dB}.
   - **Transient Response (2kHz, 1V_{pp}):** Observe input vs. output sine waves.

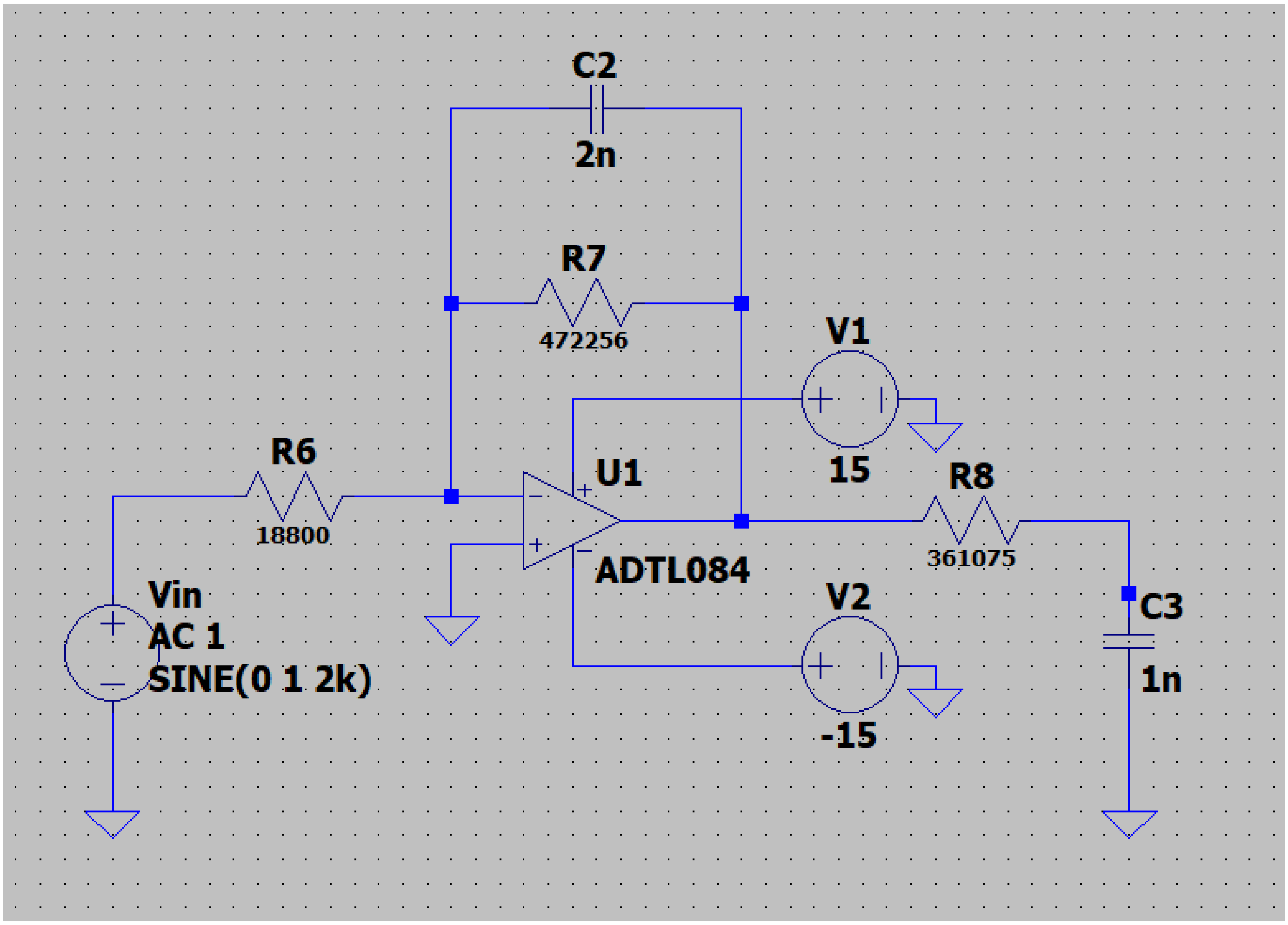


Figure 1: 2nd Order Low Pass Filter

1.3 Simulation results

Sr. No.	Parameter	Value
1	R_6	18.8kΩ
2	R_7	472.256kΩ
3	R_8	361kΩ
4	C_2	2nF
5	C_3	1nF

Table 1: Parameter Values

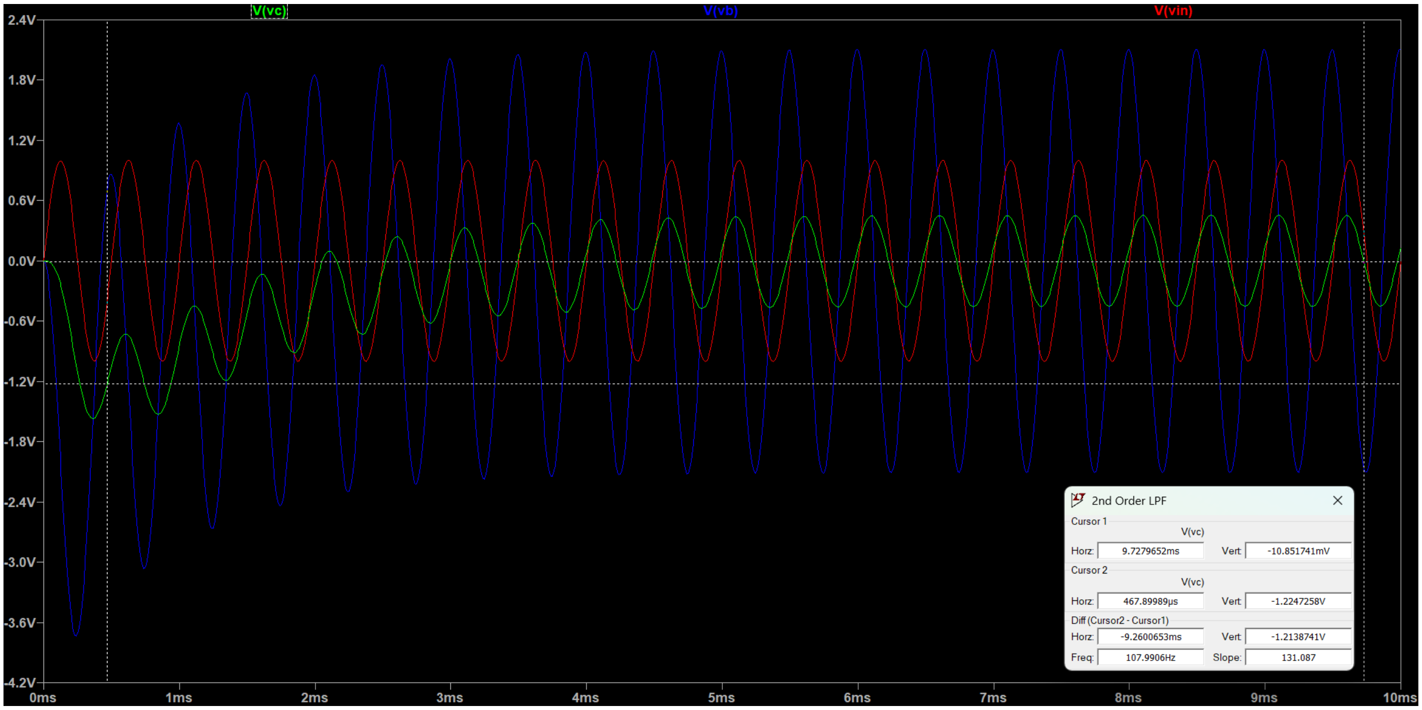


Figure 2: AC Analysis

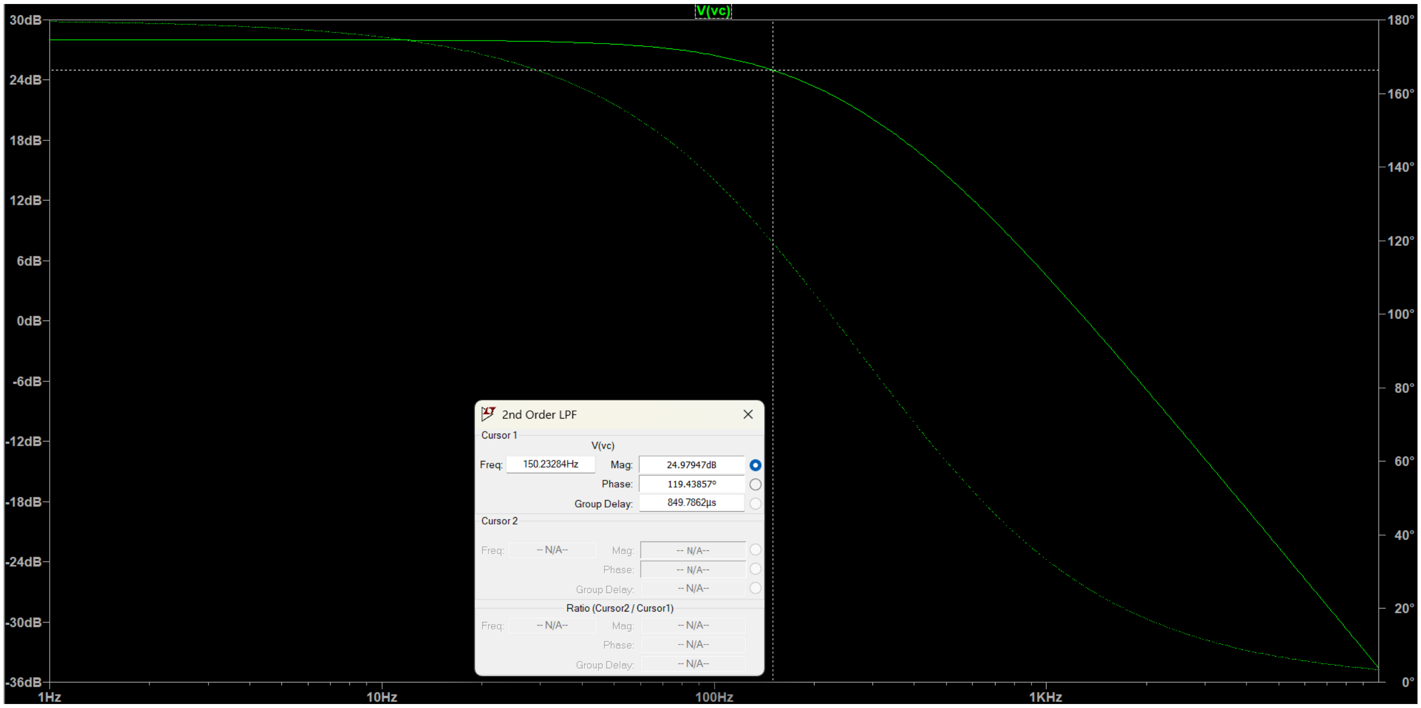


Figure 3: Transient Analysis

1.4 Conclusions

1. **DC Gain:** $\sim$ 28dB (measured)
2. **3dB Cutoff:** $\sim$150Hz
3. **Transient Behavior:** Attenuation of high-frequency components; clean sine at output with expected amplitude scaling.

Thus, the designed filter meets the specifications, providing the desired gain and cutoff, and behaves as a stable 2nd-order low-pass stage.

2 50Hz Notch Filter

2.1 Aim

Implement and simulate a twin-T notch filter that suppresses 50Hz interference by combining:

1. A **low-pass section** (cutoff 20–30Hz)
2. A **high-pass section** (cutoff 80–90Hz)
3. **Summing network to notch** at **50Hz**

2.2 Design

1. **Low-Pass Filter (LPF):**
   - Single-pole RC: $f_{c,LP} = \frac{1}{2\pi R_9 C_6} \rightarrow$ choose R_9 for 25Hz cutoff.
   - With $C_6 = 220nF$, we get $R_9 = 28.397k\Omega$.
   - **AC Analysis (1Hz–1kHz):** Plot voltage across C_6.
2. **High-Pass Section (HPF):**
   - Single-pole RC: $f_{c,HP} = \frac{1}{2\pi R_{10} C_4} \rightarrow$ choose R_9 for 85Hz cutoff.
   - With $C_4 = 100nF$, we get $R_{10} = 18.724k\Omega$.
   - **AC Analysis (0.1Hz–1kHz):** Plot voltage across R_{10}.
3. **Notch Network:**
   - Combine LPF output and inverted HPF output (twin-T topology).
   - **AC Analysis (0.1Hz–1kHz):** Plot V_{out}; tabulate notch depth and half-power frequencies around notch.

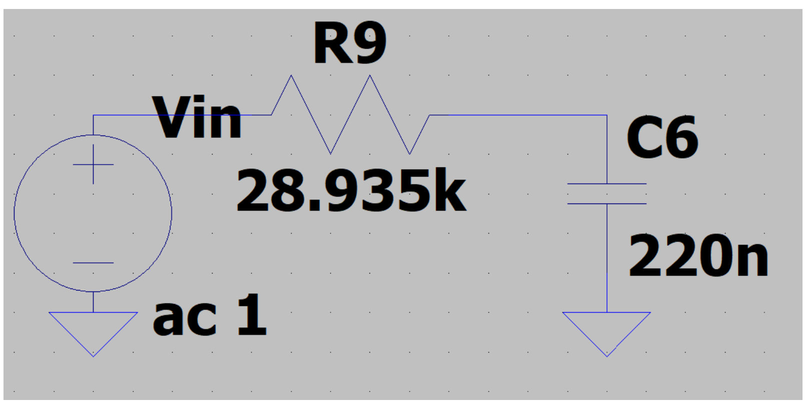


Figure 4: The Low-Pass Filter

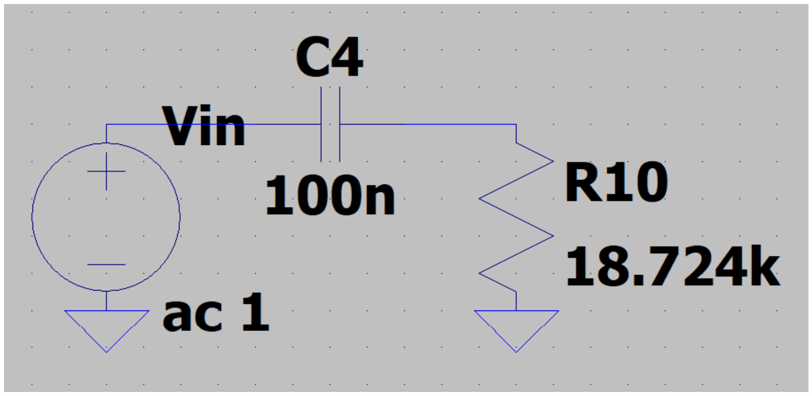


Figure 5: The High-Pass Filter

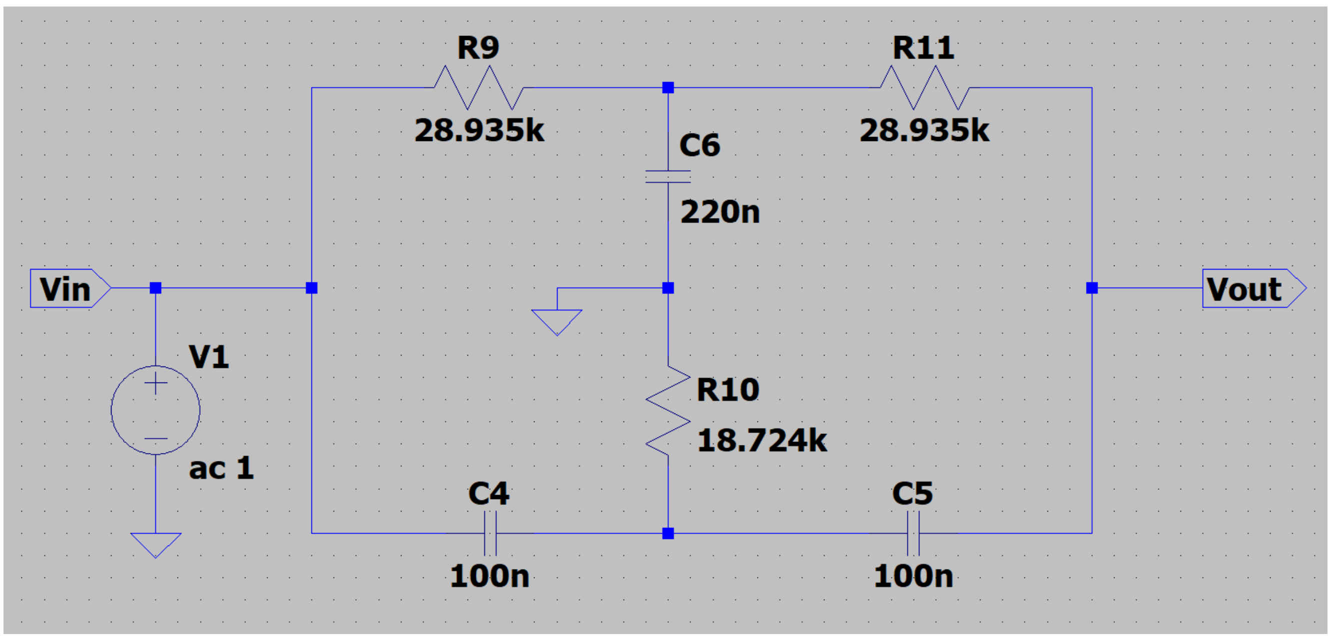


Figure 6: The High-Pass Filter

2.3 Simulation results

Sr. No.	Parameter	Value
1	R_9	28.935kΩ
2	C_6	$220nF$
3	R_{10}	18.724kΩ
4	C_4	$100nF$

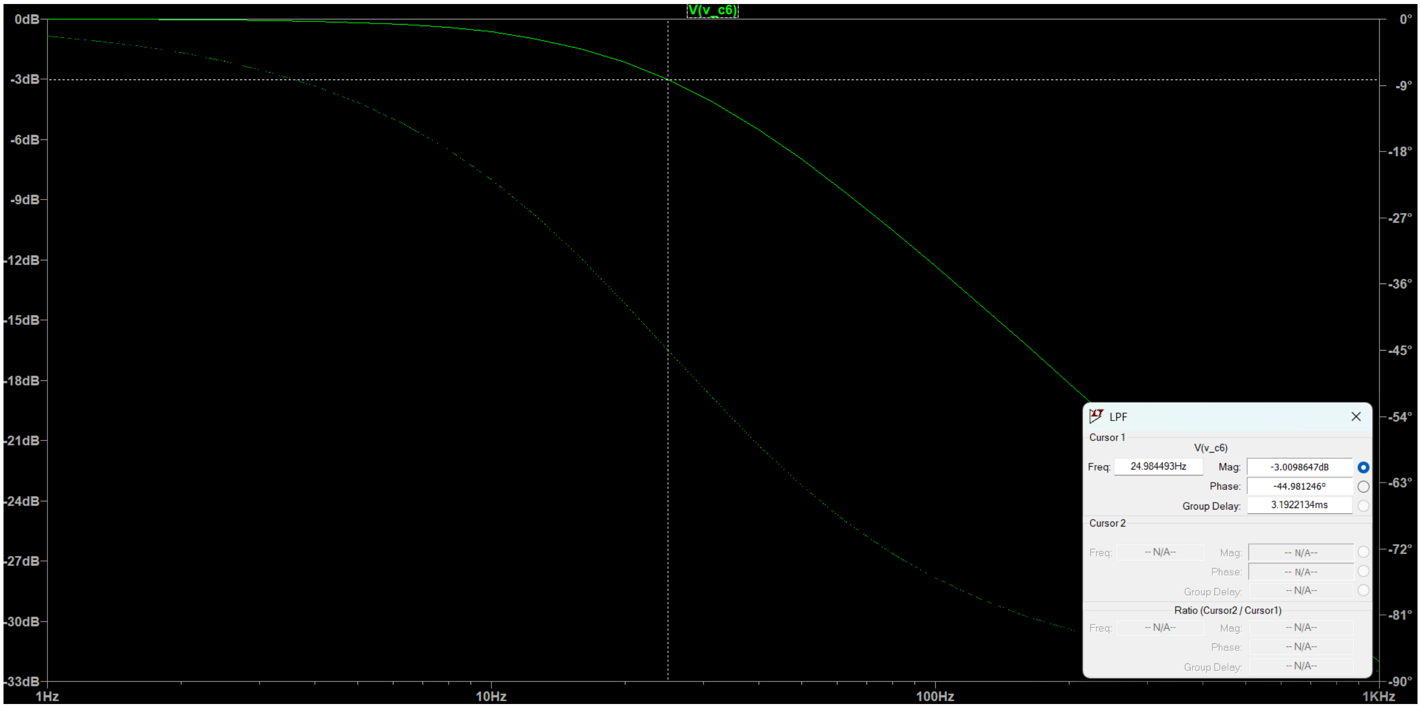


Figure 7: The Low-Pass Filter Characteristics

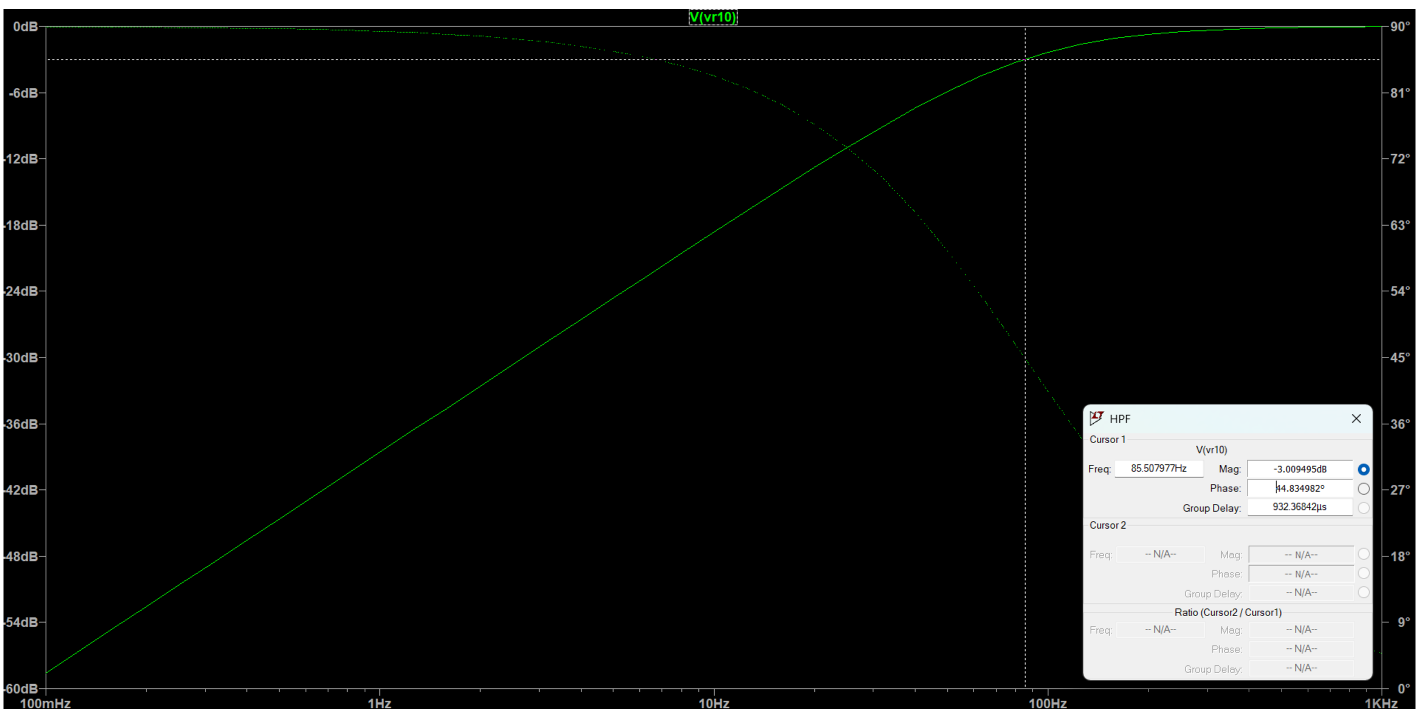


Figure 8: The High-Pass Filter Characteristics

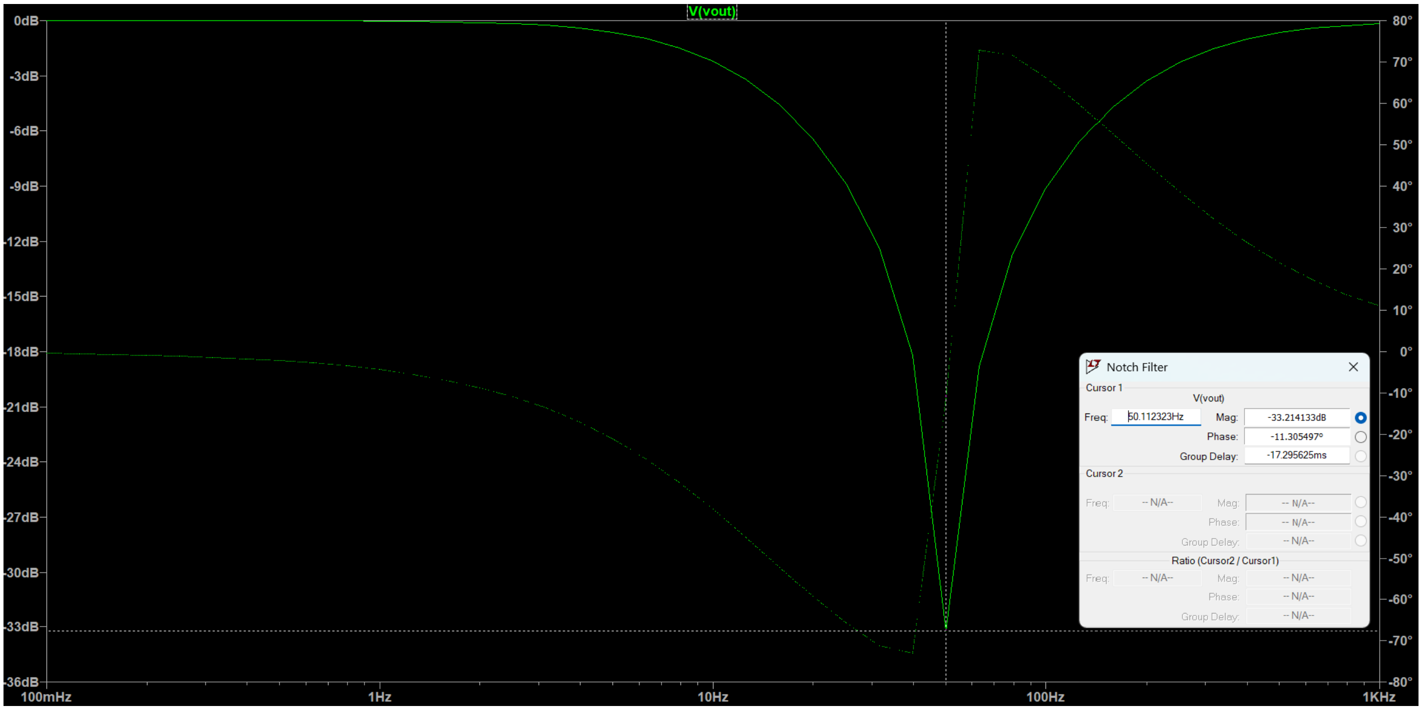


Figure 9: The Notch Characteristics

2.4 Conclusions

1. **LPF Cutoff:** 24.98Hz $\sim$ 25Hz
2. **HPF Cutoff:** 85.5Hz $\sim$ 85Hz
3. **Notch Depth:** 30dB attenuation at 50Hz
4. **Bandwidth Around Notch:** $\sim \pm$ 5Hz

The twin-T network effectively rejects 50Hz interference while passing frequencies outside the notch with minimal distortion.

3 Combined Response of LPF + Notch

3.1 Aim

Integrate the 2nd-order low-pass filter (Part (a)) with the 50Hz notch filter (Part (b)) and characterize the overall ECG amplifier response:

1. Measure DC gain and overall 3dB cutoff
2. Verify transient responses at representative frequencies (20Hz, 50Hz, 100Hz, 2kHz)

3.2 Design

1. **Topology:** Cascade of Part(a) filter into Part(b) notch network.
2. **AC Analysis (0.1Hz–1kHz):**
   - Plot combined V_{out}
   - Extract overall DC gain (∼28dB) and 3dB cutoff (∼150Hz).
3. **Transient Simulations:**
   - **20Hz:** Low-frequency ECG component passes with correct gain.
   - **50Hz:** Notch yields deep attenuation in time-domain.
   - **100Hz & 2kHz:** Observe roll-off per low-pass behavior; high-frequency suppression.

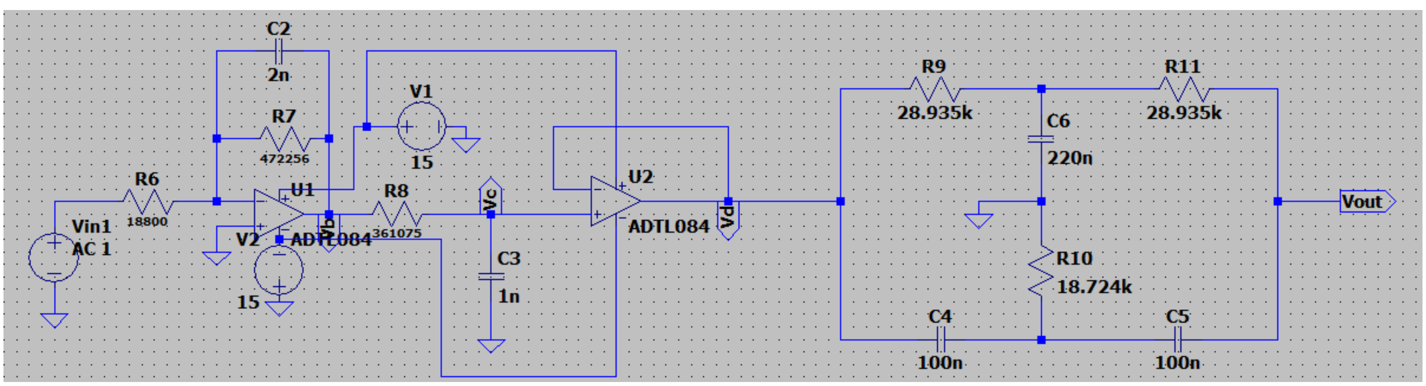


Figure 10: The Combined Circuit

3.3 Simulation results

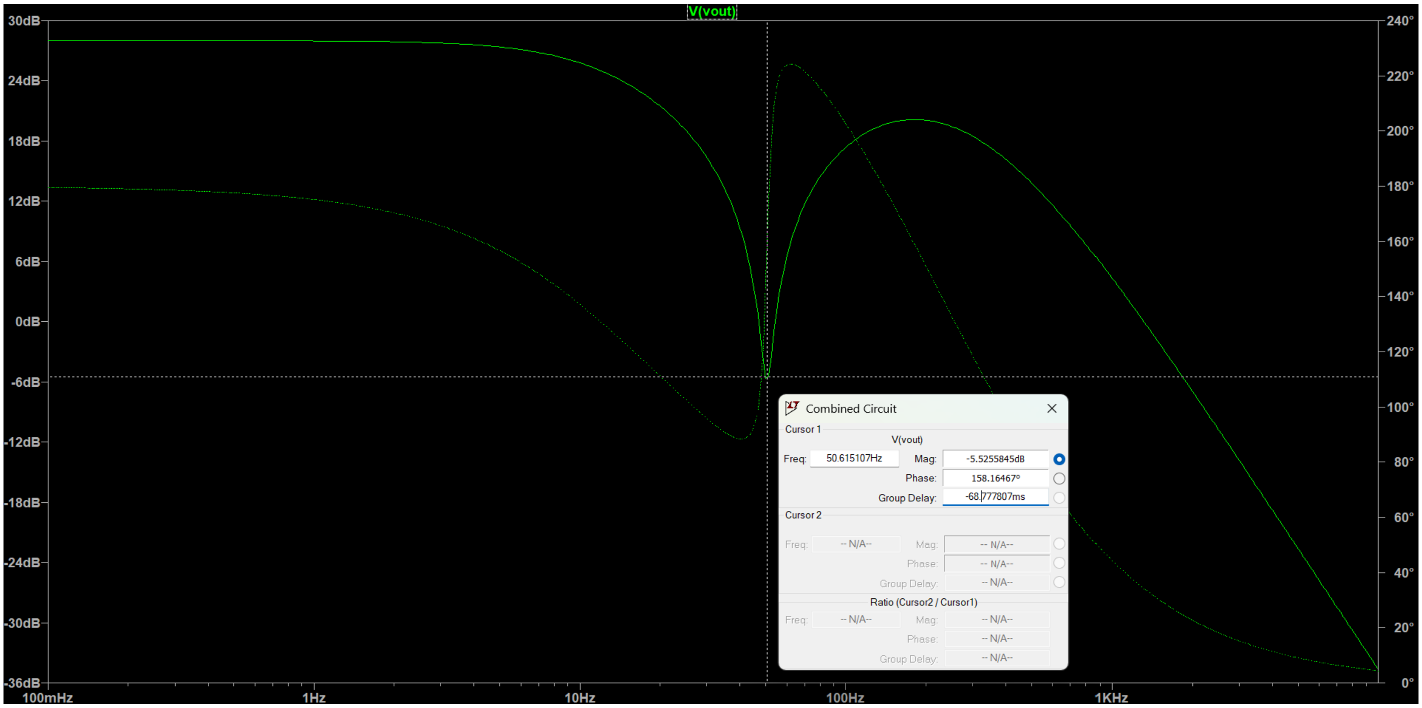


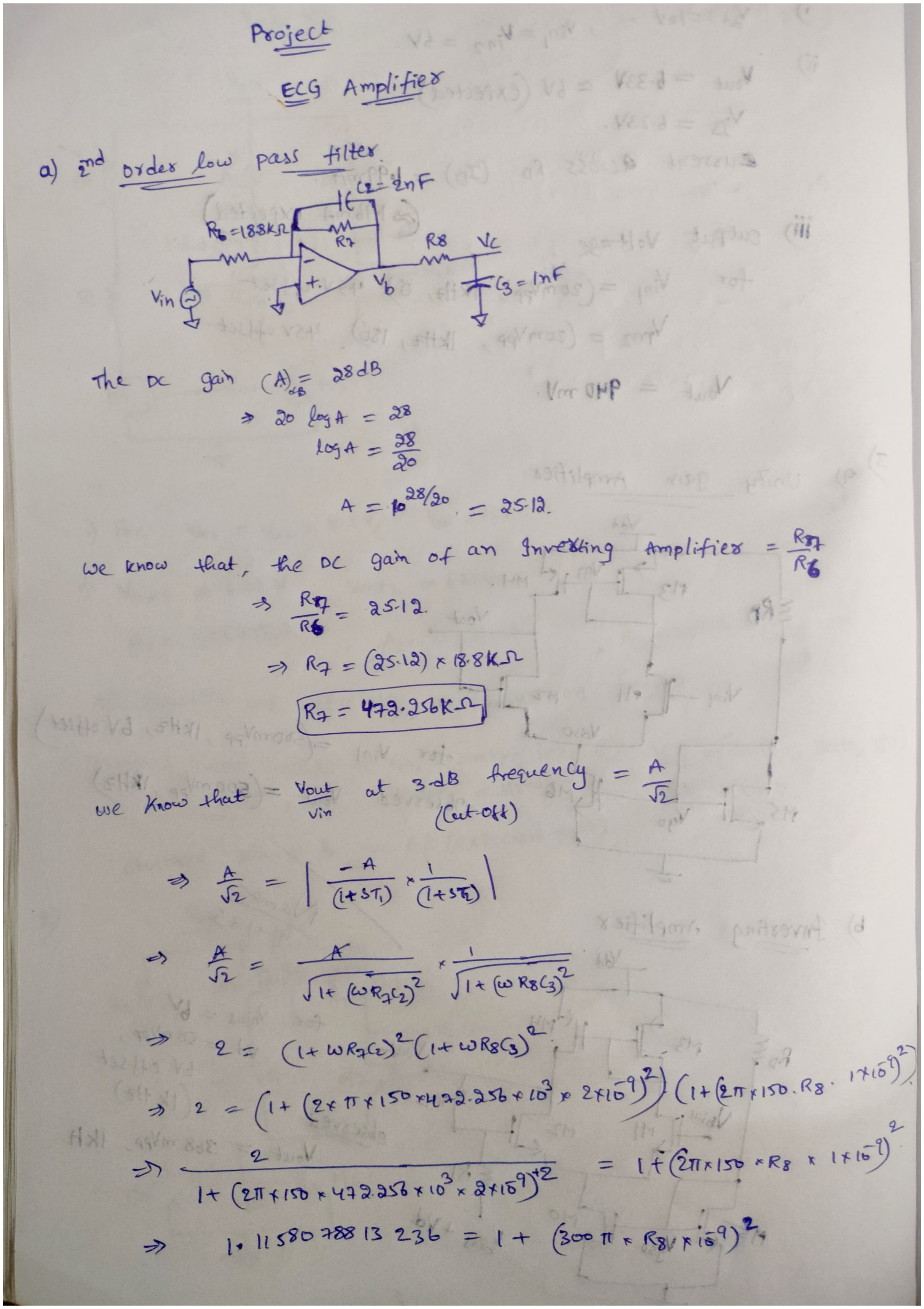
Figure 11: The Combined Circuit Characteristics

3.4 Conclusions

1. **Overall DC Gain:** ∼ 28dB
2. **Overall 6dB Cutoff:** ∼ 150Hz
3. **Transient Observations:**
   - **20 Hz:** Clean amplification. **50 Hz:** Nearly zero output (notch action) **100 Hz** & **2 kHz:** Progressive attenuation per filter roll-off.

The combined amplifier meets ECG signal requirements: high gain in passband (0.5–150Hz), strong 50Hz rejection, and suppression of unwanted high-frequency noise.

4 Calculations



Project

ECG Amplifier

a) 2nd order low pass filter

The DC gain $(A)_{dB} = 28\,dB$

$$\Rightarrow 20 \log A = 28$$

$$\log A = \frac{28}{20}$$

$$A = 10^{28/20} = 25.12$$

We know that, the DC gain of an Inverting Amplifier $= \frac{R_7}{R_6}$

$$\Rightarrow \frac{R_7}{R_6} = 25.12$$

$$\Rightarrow R_7 = (25.12) \times 18.8 k\Omega$$

$$\boxed{R_7 = 472.256 k\Omega}$$

We know that $\frac{V_{out}}{V_{in}}$ at 3 dB frequency (cut-off) $= \frac{A}{\sqrt{2}}$

$$\Rightarrow \frac{A}{\sqrt{2}} = \left| \frac{-A}{(1+sT_1)} \times \frac{1}{(1+sT_2)} \right|$$

$$\Rightarrow \frac{A}{\sqrt{2}} = \frac{A}{\sqrt{1+(\omega R_7 C_2)^2}} \times \frac{1}{\sqrt{1+(\omega R_8 C_3)^2}}$$

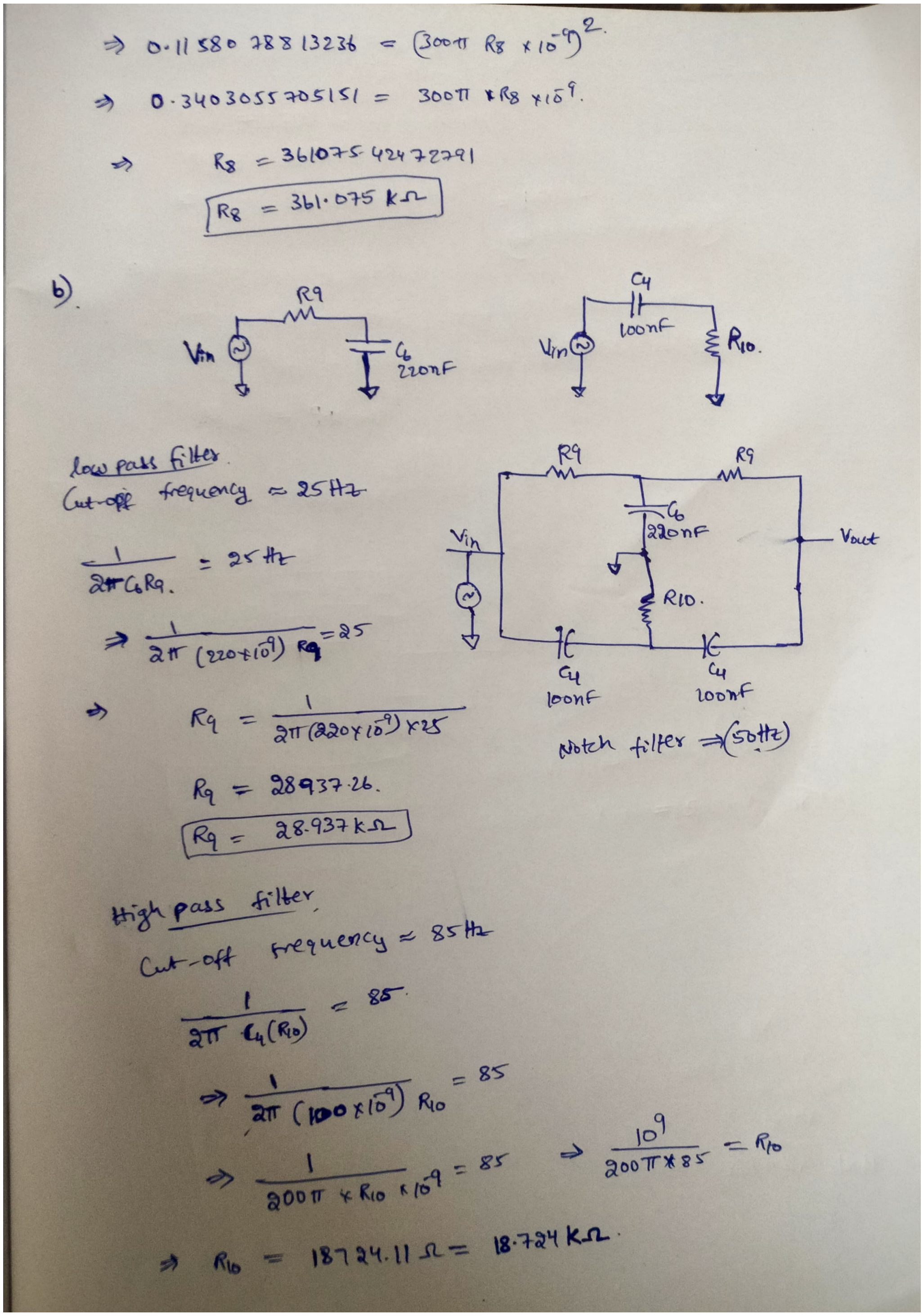
$$\Rightarrow 2 = (1+\omega R_7 C_2)^2 (1+\omega R_8 C_3)^2$$

$$\Rightarrow 2 = \left(1+(2\times\pi\times150\times472.256\times10^3\times2\times10^{-9})^2\right)\left(1+(2\pi\times150 . R_8 \cdot 1\times10^{-9})^2\right)$$

$$\Rightarrow \frac{2}{1+(2\pi\times150\times472.256\times10^3\times2\times10^{-9})^2} = 1+(2\pi\times150\times R_8\times1\times10^{-9})^2$$

$$\Rightarrow 1.1158078813236 = 1 + (300\pi \times R_8 \times 10^{-9})^2$$

Figure 12: Calculations 1



$\Rightarrow 0.1158078813236 = (300\pi R_8 \times 10^{-9})^2.$

$\Rightarrow 0.3403055705151 = 300\pi \times R_8 \times 10^{-9}.$

$\Rightarrow R_8 = 361075.42472791$

$\boxed{R_8 = 361.075\ k\Omega}$

b).

low pass filter.

Cut-off frequency ≈ 25Hz

$\frac{1}{2\pi C_6 R_9} = 25\ Hz$

$\Rightarrow \frac{1}{2\pi(220\times10^{-9})R_9} = 25$

$\Rightarrow R_9 = \frac{1}{2\pi(220\times10^{-9})\times25}$

$R_9 = 28937.26.$

$\boxed{R_9 = 28.937\ k\Omega}$

Notch filter ⇒ (50Hz)

High pass filter.

Cut-off frequency ≈ 85Hz

$\frac{1}{2\pi C_4(R_{10})} = 85.$

$\Rightarrow \frac{1}{2\pi(100\times10^{-9})R_{10}} = 85$

$\Rightarrow \frac{1}{200\pi \times R_{10} \times 10^{-9}} = 85 \quad \Rightarrow \frac{10^9}{200\pi \times 85} = R_{10}$

$\Rightarrow R_{10} = 18724.11\ \Omega = 18.724\ k\Omega.$

Figure 13: Calculations 2