OMD551 - BASICS OF BIOMEDICAL INSTRUMENTATION

UNIT III SIGNAL CONDITIONING CIRCUITS

Need for bio-amplifier - differential bio-amplifier, Impedance matching circuit, isolation amplifiers, Power line interference, Right leg driven ECG amplifier, Band pass filtering

3.1 Need for Bio-amplifier:

Generally, biological/bioelectric signals have low amplitude and low frequency. Therefore, to increase the amplitude level of biosignals amplifiers are designed. The outputs from these amplifiers are used for further analysis and they appear as ECG, EMG, or any bioelectric waveforms. Such amplifiers are defined as Bio Amplifiers or Biomedical Amplifiers.

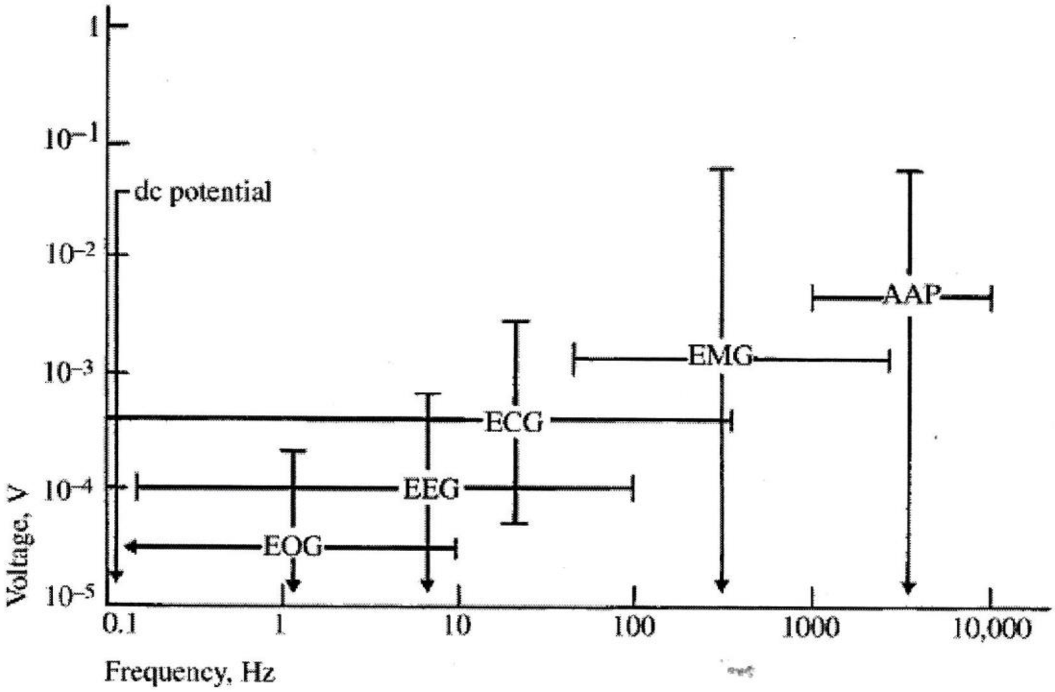
Basic Requirements for Biological Amplifiers

1. The **biological amplifier** should have a high input impedance value. The range of value lies between 2 MΩ and 10 MΩ depending on the applications. Higher impedance value reduces distortion of the signal.
2. When electrodes pick up biopotentials from the human body, the input circuit should be protected. Every bio-amplifier should consist of isolation and protection circuits, to prevent the patients from electrical shocks.
3. Since the output of a bioelectric signal is in millivolts or microvolt range, the voltage gain value of the amplifier should be higher than 100dB.
4. Throughout the entire bandwidth range, a constant gain should be maintained.
5. A bio-amplifier should have a small output impedance.
6. A good bio-amplifier should be free from drift and noise.
7. Common Mode Rejection Ratio (CMRR) value of amplifier should be greater than 80dB to reduce the interference from common mode signal.
8. The gain of the bio-amplifier should be calibrated for each measurement.

Types of Bio Amplifiers

1. Differential Amplifier
2. Operational Amplifier
3. Instrumentation Amplifier
4. Chopper Amplifier
5. Isolation Amplifier

Voltage and Frequency ranges of Some common Bio potential Signals:



The above figure shows the ranges of amplitude and frequencies covered by several of the common bio potential signals. Depending on the signal frequency ranges from dc to about 10 kHz. Amplitudes can range from tens of microvolts to approximately 100micro volts. the amplifier for a particular bio potential must be designed to handle that potential and to provide an appropriate signal at its output.

3.2 Differential Amplifier

Medical amplifiers designed for use in the input stage (preamplifiers) are mostly of the differential type. These type have three input terminals out of which one is arranged at the reference potential and the other two are live terminals.

The differential amplifier is employed when it is necessary to measure the voltage difference between two points, both of them varying in amplitude at different rates and in different patterns.

Heart-generated voltages picked up by means of electrodes on the arms and legs, and brain-generated voltages picked up by the electrodes on the scalp are typical examples of signals whose measurement requires the use of differential amplifiers.

The differential amplifier is an excellent device for use in the recording systems. Its excellence lies in its ability to reject common-mode interference signals which are invariably picked up by electrodes from the body along with the useful bioelectric signals.

Also, as a direct coupled amplifier, it has good stability and versatility. High stability is achieved because it can be insensitive to temperature changes which is often the source of excessive drift in other configurations.

It is versatile in that it may be adapted for a good many applications, e.g. applications requiring floating inputs and outputs or for applications where grounded inputs and/or outputs are desirable.

Figure 1 shows such a circuit made of two BJTs (Q_1 and Q_2) and two power supplies of opposite polarity viz., V_{CC} and $-V_{EE}$ which uses three resistors among which two are the collector resistors, R_{C1} and R_{C2} (one for each transistor) while one is the emitter resistor R_E common to both transistors.

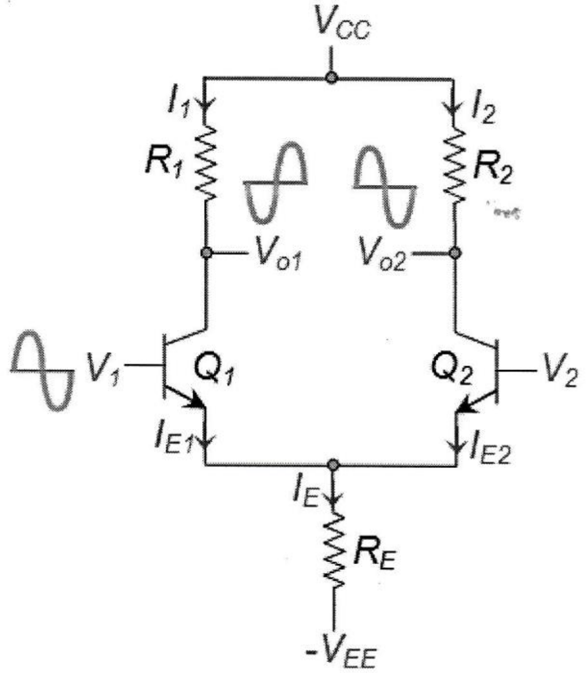


Figure 1 A BJT Differential Amplifier

In this case, if the V_1 at Q_1 is sinusoidal, then as V_1 goes on increasing, the transistor starts to conduct and this results in a heavy collector current I_{C1} increasing the voltage drop across R_{C1}, causing a decrease in V_{o1}. Due to the same effect, even I_{E1} increases which increases the common emitter current, I_E resulting in an increase of voltage drop across R_E.

This means that the emitters of both transistors are driven towards positive which inturn implies that the base of Q_2 would start to become more and more negative. This results in a decrease of collector current, I_{C2} which inturn decreases the voltage drop across the collector resistor R_{C2}, resulting in an increase in the output voltage V_{o2}. This indicates that the changes in the sinusoidal signal observed at the input of transistor Q_1 is reflected as such across the collector terminal of Q_2 and appear with a phase difference of 180° across the collector terminal of Q_1. The differential amplification can be driven by considering the output in-between the collector terminals of the transistors, Q_1 and Q_2.

On the other hand, if the signal applied to each input terminal is equal in amplitude and is in the same phase (called the common-mode input signal), the change in current flow through both transistors will be identical, the bridge will remain balanced, and the voltage between the output terminals will remain zero. Thus, the circuit provides high gain for differential mode signals and no output for all common mode signals.

The ability of the amplifier to reject these common voltages on its two input leads is known as common-mode rejection and is specified as the ratio of common-mode input to differential input to elicit the same response. It is abbreviated as CMRR (Common-mode rejection ratio).

CMRR is an important specification referred to the differential amplifier and is normally expressed as decibels. CMRR of the preamplifiers should be as high as possible so that only the wanted signals find a way through the amplifier and all unwanted signals get rejected in the preamplifier stage.

3.2.1 Op-amp Differential Amplifier:

The design of a good differential amplifier essentially implies the use of closely matched components which has been best achieved in the integrated circuit form. High gain integrated dc amplifiers, with differential input connections and a provision for external feedback have been given the name operational amplifiers because of their ability to perform mathematical operations.

These amplifiers are applied for the construction of ac or dc amplifiers, active filters, phase inverters, multivibrators and comparators, etc. by suitable feedback arrangement, and therefore find a large number of applications in the medical field.

Figure 3 shows a single op-amp in a differential amplifier configuration.

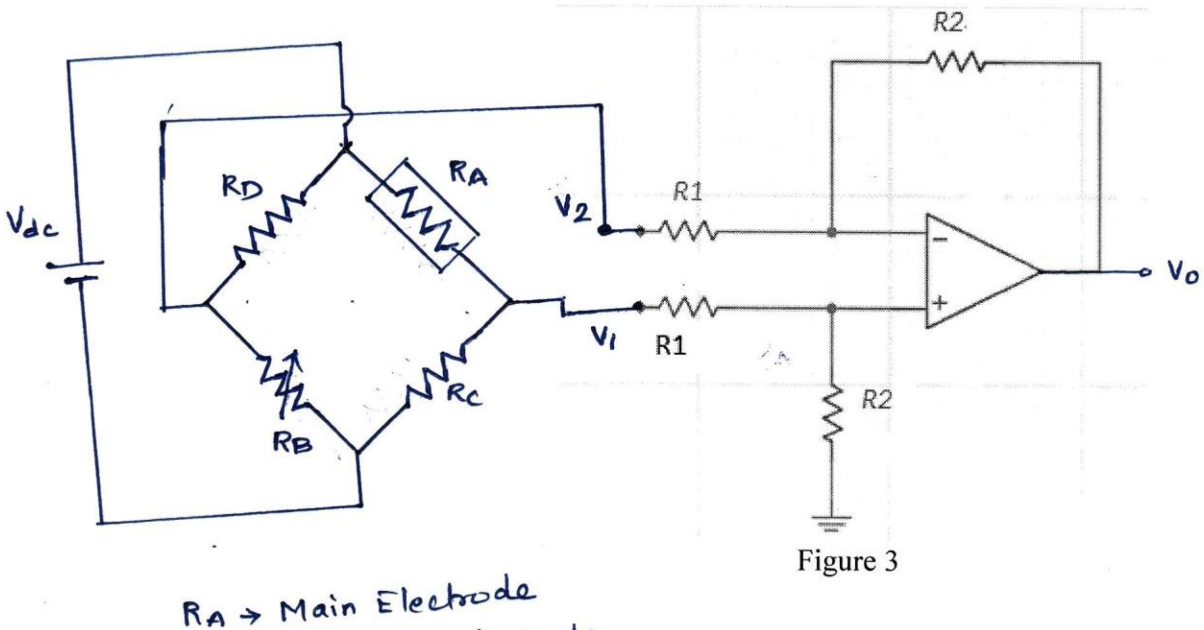


Figure 3

RA → Main Electrode
RB → Reference Electrode

Input V_1=0, the circuit act as a inverting amplifier. So the output of inverting amplifier

$$V_{01} = -\frac{R_2}{R_1} V_1$$

If the input V_1 =0 ,the circuit act as a Non inverting amplifier. The voltage at the non-inverting terminal

$$V_N = V_2 \frac{R_2}{R_1 + R_2}$$

The non inverting amplifier output is

$$V_{02} = \left(1 + \frac{R_2}{R_1}\right) V_N$$

The total output voltage of differential amplifier,

$$V_0 = V_{01} + V_{02}$$

$$V_0 = -\frac{R_2}{R_1} V_1 + \left(1 + \frac{R_2}{R_1}\right) V_N$$

$$V_0 = -\frac{R_2}{R_1} V_1 + \left(1 + \frac{R_2}{R_1}\right) V_2 \frac{R_2}{R_1 + R_2}$$

$$V_0 = \frac{R_2}{R_1} (V_1 - V_2)$$

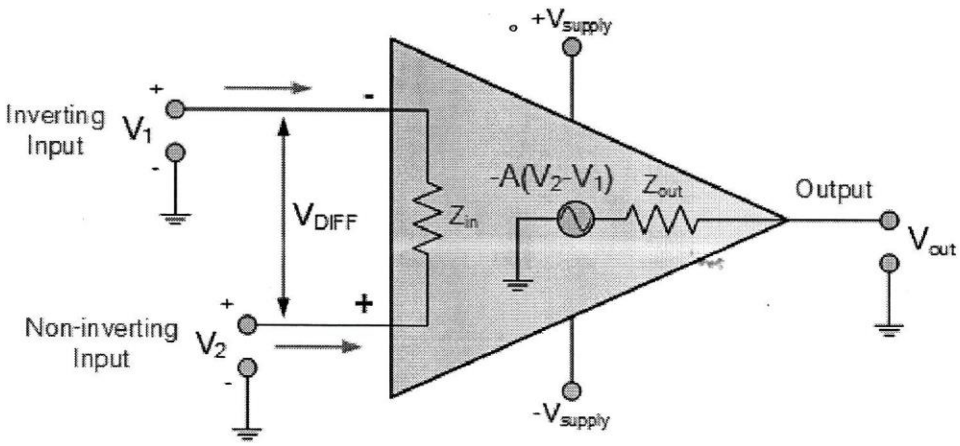
The common mode rejection for most op-amps is typically between 60 dB and 90 dB. This may not be sufficient to reject common mode noise generally encountered in biomedical measurements. Also, the input impedance is not very high to handle signals from high impedance sources. One method to increase the input impedance of the op-amp is to use field effect transistors (FET) in the input differential stage. A more common approach is to use an instrumentation amplifier in the preamplifier stage.

3.3 Operational Amplifier Configurations:

An Op-amp is a high gain differential amplifier. The best way to approach the design of a circuit that uses Op-amp is first to assume that the Op-amp is ideal.

Ideal Characteristics:

An Op-amp ideal equivalent circuit is shown in the figure.



The voltage at the inverting input terminal V_1 and Non inverting input terminal V_2.The voltage difference at the input side $V_d=V_2-V_1$.
Op-amp output voltage $V_0= A(V_2-V_1)$.

Ideal Op-amp Characteristics:

Ideal Op-amp characteristics are given below. The values are compared with practical Op-amp.

Parameter	Ideal Op-amp	Typical Op-amp
Differential Voltage Gain	∞	10^5-10^9
Common mode Voltage gain	0	10^{-5}
Input resistance	∞	10^6
Output resistance	0	100-1000 Ω
Bandwidth	∞	Few MHz
Offset Voltage and Current	0	Few Microvolts and micro amps

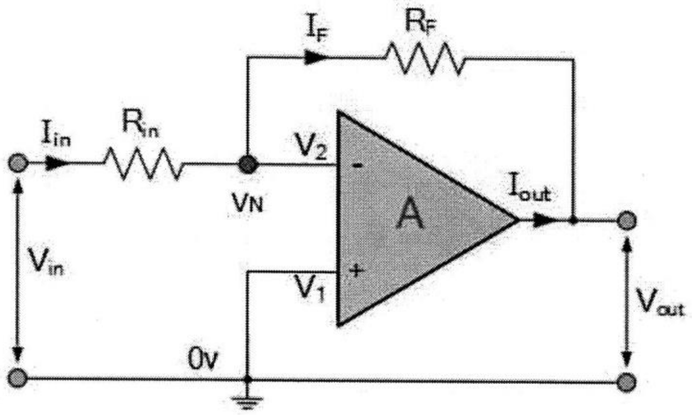
Inverting Amplifier:

While on the one hand, operational amplifiers offer very high gain, it makes the amplifier unstable & hard to control. Some of this gain can be lost by connecting a resistor across the amplifier from the output terminal back to the inverting input terminal to control the final gain of the amplifier. This is commonly known as negative feedback and produces a more stable op-amp.

Negative feedback is the process of feeding a part of the output signal back to the input. But to make the feedback negative, it is fed to the negative or "inverting input" terminal of the op-amp using a resistor. This effect produces a closed loop circuit resulting in Closed-loop Gain. A closed-loop inverting amplifier uses negative feedback to accurately control the overall gain of the amplifier, but causes a reduction in the amplifiers gain

In an inverting amplifier circuit, the operational amplifier inverting input receives feedback from the output of the amplifier. Assuming the op-amp is ideal and applying the concept of virtual short at the input terminals of op-amp, the voltage at the inverting terminal is equal to non-inverting terminal. The non-inverting input of the operational amplifier is connected to ground.

As the gain of the op amp itself is very high and the output from the amplifier is a matter of only a few volts, this means that the difference between the two input terminals is exceedingly small and can be ignored. As the non-inverting input of the operational amplifier is held at ground potential this means that the inverting input must be virtually at earth potential.



Derive the output voltage expression of this inverting amplifier, V_N=0, Due to Virtual Ground.

$$I_{in} = I_F$$

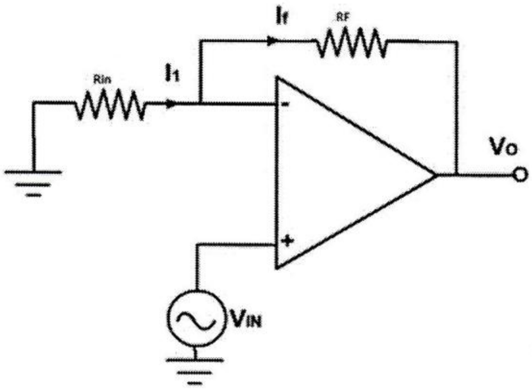
$$\frac{V_{in}-V_N}{R_{in}} = \frac{V_N-V_{out}}{R_F}$$

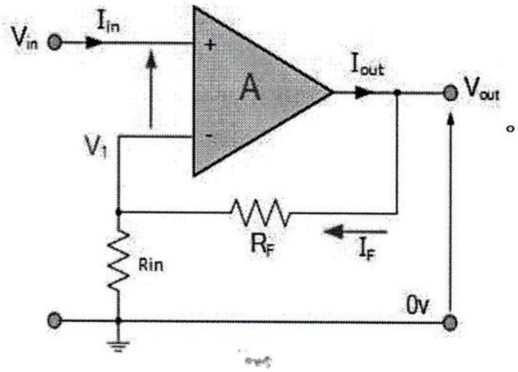
$$V_{out} = -\frac{R_F}{R_{in}} V_{in}$$

$$Gain\ A = \frac{R_F}{R_{in}}$$

Non-Inverting Amplifier:

The non-inverting amplifier is one in which the output is in phase with respect to the input. The feedback is applied at the inverting input. However, the input is now applied at the non-inverting input. The output is a non-Inverted (in terms of phase) amplified version of input. The gain of the non-inverting amplifier circuit for the operational amplifier is easy to determine.





Just rotate inverting and non-inverting terminal

$$V_1 = V_{in}$$

$$V_{in} = V_{out}\,\frac{R_{in}}{R_F + R_{in}}$$

$$V_{out} = V_{in}\,\frac{R_F + R_{in}}{R_{in}}$$

$$V_{out} = V_{in}\,(1 + \frac{R_F}{R_{in}})$$

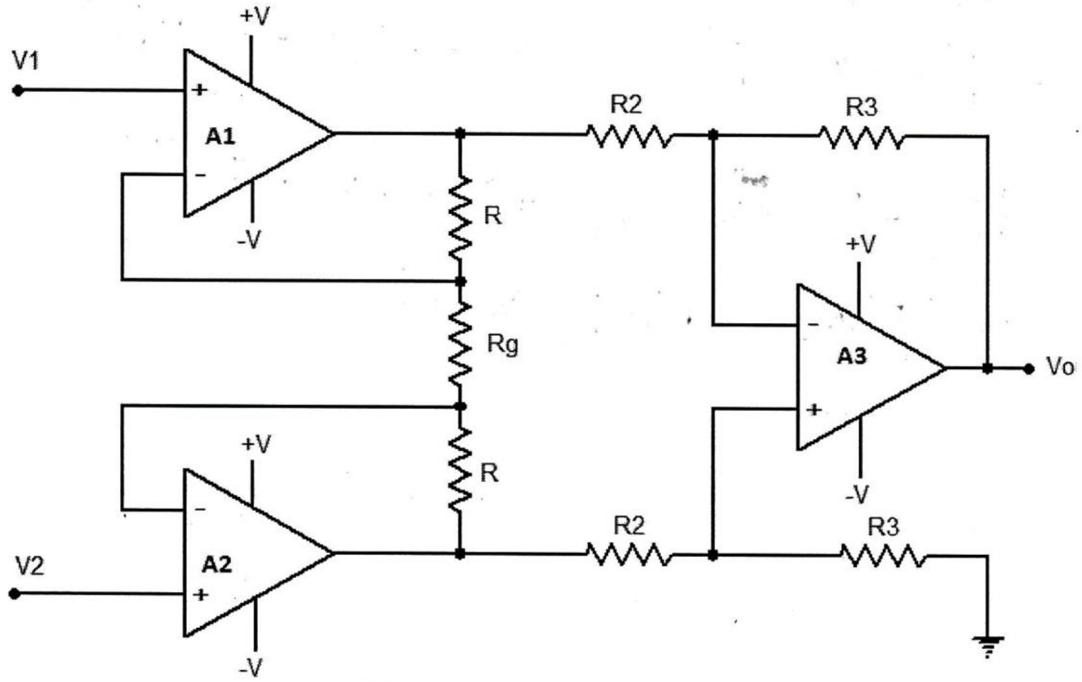
$$Gain\ A = (1 + \frac{R_F}{R_{in}})$$

3.4 Impedance matching circuit:

Instrumentation Amplifier:

Instrumentation amplifier is a kind of differential amplifier with additional input buffer stages. **The addition of input buffer stages makes it easy to match (impedance matching) the amplifier with the preceding stage**. Instrumentation are commonly used in industrial test and measurement application.

The instrumentation amplifier also has some useful features like low offset voltage, high CMRR (Common mode rejection ratio), high input resistance, high gain etc. The circuit diagram of a typical instrumentation amplifier using opamp is shown below.



INSTRUMENTATION AMPLIFIER

A circuit providing an output based on the difference between two inputs (times a scale factor) is given in the above figure. In the circuit diagram, opamps labelled A1 and A2 are the input buffers. Anyway the gains of these buffer stages are not unity because of the presence of R' and Rg. Op amp labelled A3 is wired as a standard differential amplifier. R3 connected from the output of A3 to its non inverting input is the feedback resistor. R2 is the input resistor. The voltage gain of the instrumentation amplifier can be expressed by using the equation below.

Op-amp A3 working as a differential amplifier. The output voltage expression of differential amplifier,

$$V_0 = \frac{R_3}{R_2}(V_2' - V_1') \quad \text{------------------------ (1)}$$

$$V_1' = -R'I + V_1 \quad \text{------------------------ (2)}$$

$$V_2' = R'I + V_2 \quad \text{------------------------ (3)}$$

Let $I = \frac{V_2 - V_1}{R_g}$

Substitute I in Eq. (2) and (3) and derive V_1' and V_2'

$$V_1' = -R'\left(\frac{V_2 - V_1}{R_g}\right) + V_1 \qquad V_2' = R'\left(\frac{V_2 - V_1}{R_g}\right) + V_2$$

$$V_1' = -\frac{R'}{R_g}V_2 + \frac{R'}{R_g}V_1 + V_1 \qquad V_2' = \frac{R'}{R_g}V_2 - \frac{R'}{R_g}V_1 + V_2$$

$$V_1' = -\frac{R'}{R_g}V_2 + V_1\left(1 + \frac{R'}{R_g}\right) \qquad V_2' = -\frac{R'}{R_g}V_1 + V_2\left(1 + \frac{R'}{R_g}\right)$$

Substitute V_1' and V_2' in Eq.(1)

$$V_0 = \frac{R_3}{R_2}\left[-\frac{R'}{R_g}V_1 + V_2\left(1 + \frac{R'}{R_g}\right) + \frac{R'}{R_g}V_2 - V_1\left(1 + \frac{R'}{R_g}\right)\right]$$

$$V_0 = \frac{R_3}{R_1}\left[\frac{R'}{R_g}(V_2 - V_1) + \left(1 + \frac{R'}{R_g}\right)(V_2 - V_1)\right]$$

$$V_0 = \frac{R_3}{R_2}\left(1 + 2\frac{R'}{R_g}\right)(V_2 - V_1)$$

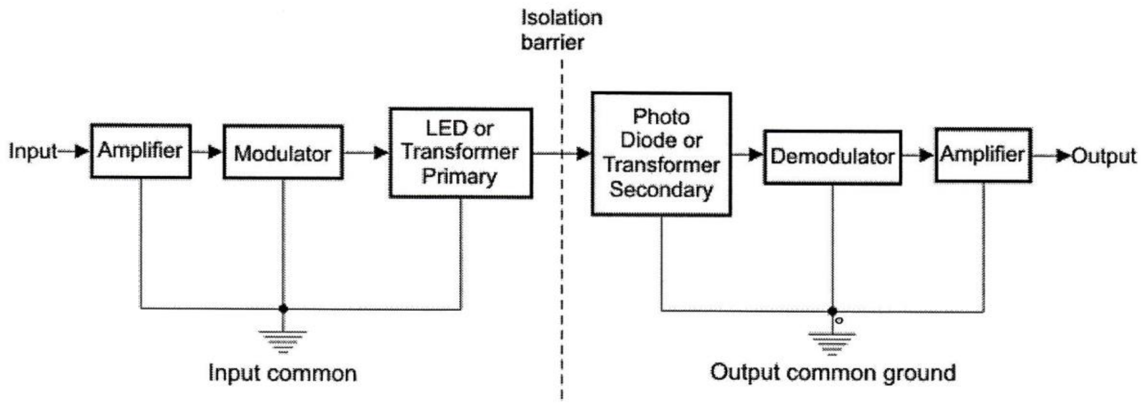
If need a setup for varying the gain, replace Rg with a suitable potentiometer. Instrumentation amplifiers are generally used in situations where high sensitivity, accuracy and stability are required.

3.5 Isolation Amplifier:

For safety, it is important to protect the user from the hazards of electrical shock. Electrical shock can always present a safety risk with electrical circuits and it is important to consider the problem seriously.

It is worth highlighting that it is current, not voltage, which is the real hazard here. Current flow in tissue can cause excessive resistive heating, leading to burns, electrochemical heating, and electrical stimulation of neuromuscular systems.

Isolation amplifiers can be used to break ground loops, eliminate source ground connections, and provide isolation protection to patient and electronic equipment. In a biopotential amplifier, the main purpose of the isolation amplifier is the protection of the patient by eliminating the hazard of electric shock resulting from the interaction among patient, amplifier, and other electric devices in the patient's environment, specifically defibrillators and electrosurgical equipment. It also adds to the prevention of line frequency interferences.



Block Diagram of Isolation Amplifier

Three methods are used in the design of isolation amplifiers: (i) transformer isolation (ii) optical isolation (iii) capacitive isolation.

(i) Transformer isolation type:

The transformer approach is shown in Fig.(3.5.1) It uses either a frequency-modulated or a pulse width modulated carrier signal with small signal bandwidths up to 30 kHz to carry the signal. It uses an internal dc–to-dc converter comprising of a 20 kHz oscillator, transformer, rectifier and filter to supply isolated power.

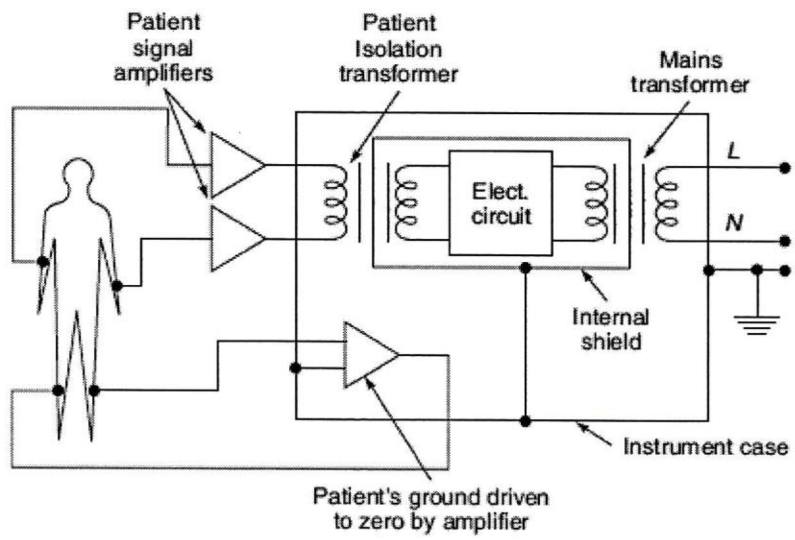


Figure 3.5.1 Transformer isolation type

(ii) Optical isolation type:

Isolation could also be achieved by optical means in which the patient is electrically connected with neither the hospital line nor the ground line. A separate battery operated circuit supplies power to the patient circuit and the signal of interest is converted into light by a light source (LED).

This light falls on a phototransistor on the output side, which converts the light signal again into an electrical signal (Fig. 3.5.2), having its original frequency, amplitude and linearity. No modulator/ demodulator is needed because the signal is transmitted optically all the way.

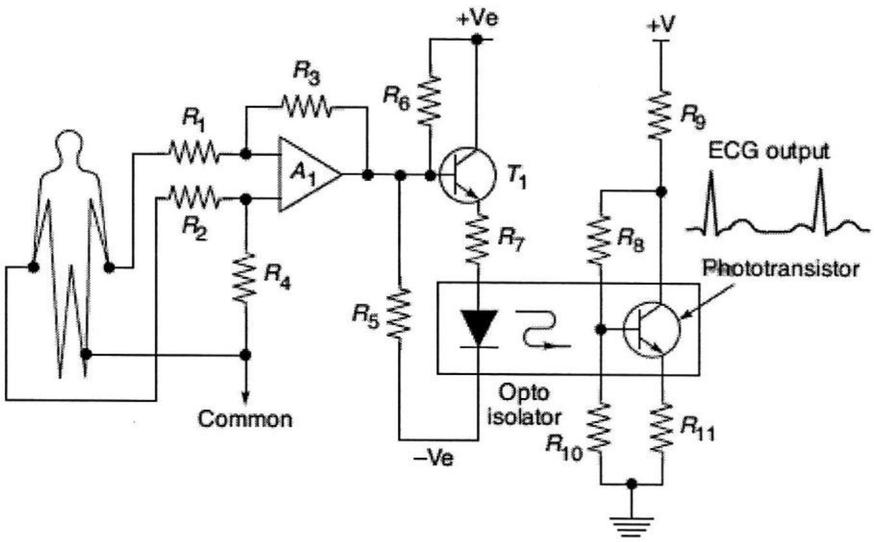
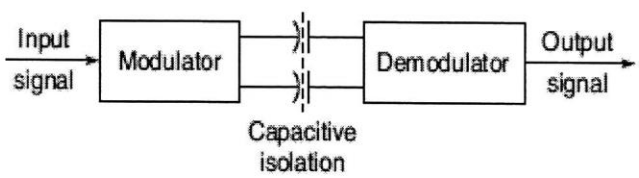


Figure 3.5.2 Optical isolation type

(iii) Capacitive isolation type:

The capacitive method (Fig. 3.5.3) uses digital encoding of the input voltage and frequency modulation to send the signal across a differential capacitive barrier. Separate power supply is needed on both sides of the barrier. Signals with bandwidths up to 70 kHz can be conveniently handled in this arrangement.



- It uses digital encoding of the input voltage and frequency modulation.
- The input voltage is converted to proportional charge on the switched capacitor.
- It has modulator and demodulator circuits.
- The signals are sent across a differential capacitive barrier.

- Separate supplies given on both sides.

Advantages:

- Ripple noises are removed.
- It avoids device noise, radiated noise and conducted noise.
- High immunity to magnetic noise.
- High gain stability and linearity.

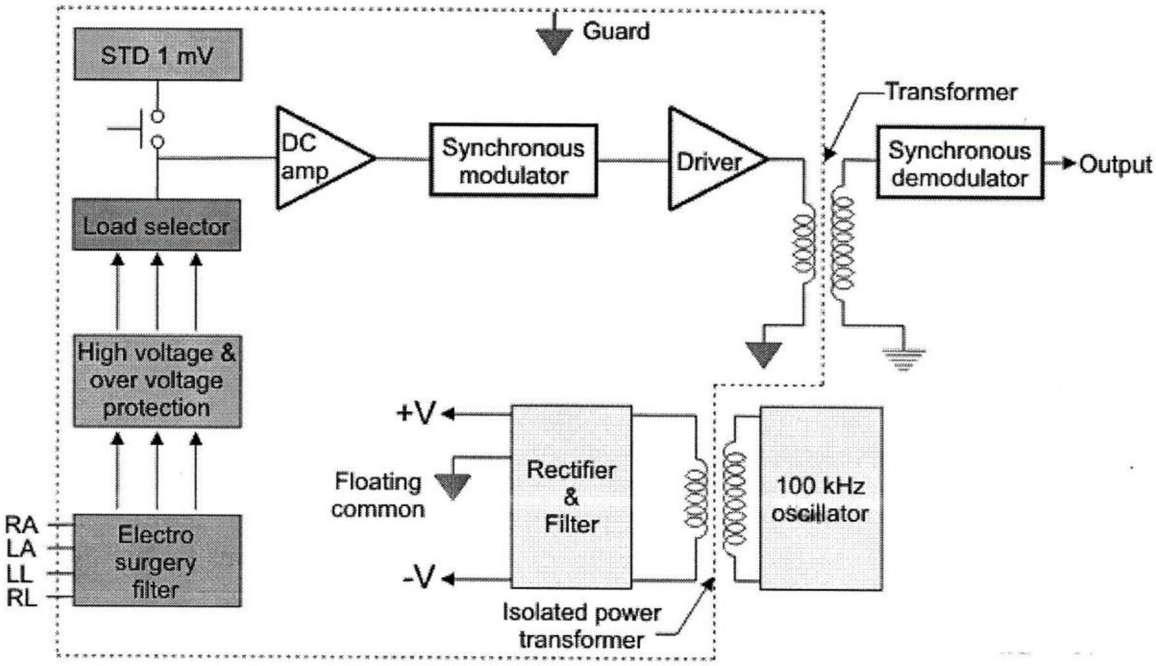
The relative merits of the three types of isolation techniques are:

- All three types are in common use, though the transformer isolation amplifier is more popular.
- Opto-coupled amplifier uses a minimum number of components and is cost effective, followed by the transformer coupled amplifier. The capacitor coupled amplifier is the most expensive.
- Opto-isolated amplifiers offer the lowest isolation voltage (800 V continuous) between input and output; transformer coupled 1200 V and capacitance coupled 2200 V.
- Isolation resistance levels are of the order of 10^{10}, 10^{12} and 10^{12} ohms for transformer coupled, opto-coupled and capacitance coupled amplifiers respectively.
- Gain stability and linearity are best for capacitance coupled versions—0.005%, and transformer and opto-coupled amplifier—0.02%.

3.6 ECG Isolation Amplifier

During ECG measurement, signals generated from all leads are sent to the low pass filter. This filter is named as Electro surgery filters because it decreases the interference between electrosurgery and radio frequency. Next block is the high voltage and overvoltage protection that can withstand large voltage during defibrillation. Proceeding further, it goes to Lead Selector Switch block, which selects the required configuration. Lead selection output goes to the DC amplifier. We have a transformer, whose primary winding is connected to the oscillator and secondary to rectifier and filter. ECG signal is modulated with the Synchronous modulator. The second transformer delivers the output from the synchronous modulator to the synchronous demodulator. The output from the demodulator is fed as input to the power amplifier.

ECG Isolation Amplifier:



3.7 Power Line Interference:

Power line interference is easily recognizable since the interfering voltage in the ECG would have a frequency of 50 Hz (Fig3.7(a)). This interference may be due to the stray effect of the alternating current on the patient or because of alternating current fields due to loops in the patient cable.

Other causes of interference are loose contacts on the patient cable as well as dirty electrodes. When the machine or the patient is not properly grounded, power line interference may even completely obscure the ECG waveform.

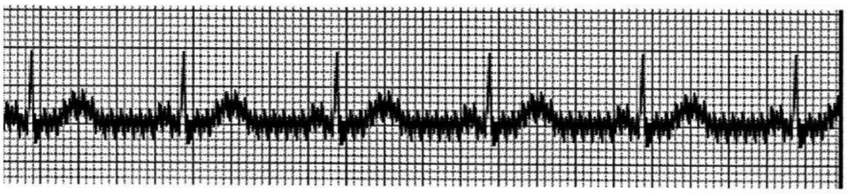


Figure 3.7 (a) ECG wave due to power line interference

The most common cause of 50 Hz interference is the disconnected electrode resulting in a very strong disturbing signal. It is often strong enough to damage the stylus of an unprotected direct writing recorder, and therefore needs quick action.

Electromagnetic interference from the power lines also results in poor quality tracings. Electrical equipment such as air-conditioners, elevators and X-ray units draw heavy power-line current, which induce 50 Hz signals in the input circuits of ECG machines. Due to unbalanced linkages, common mode rejection circuits almost prove ineffective against them.

A practical solution to minimize this problem is physical separation between the interference causing sources and the patient. Levkov *et al* (1984) developed a method of digital 50 Hz interference elimination by computing the interference amplitudes and subtracting these data from the original signal, thereby greatly reducing the requirements of amplifiers, shielding, earthing, electrode quality and application procedures.

Electrical power systems also induce extremely rapid pulses or spikes on the trace, as a result of switching action. Use of a transient suppressor in the mains lead of the machines helps to solve this problem.

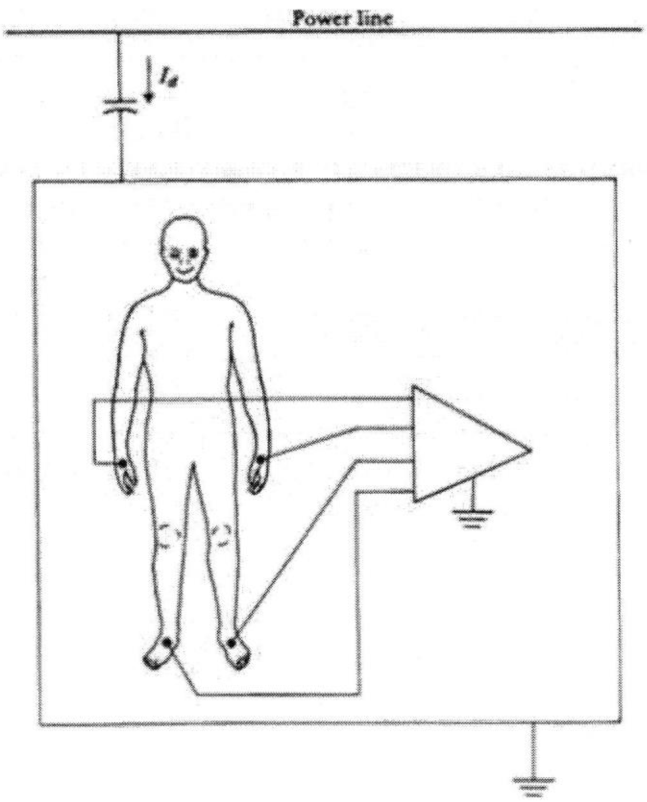
Shielding techniques to eliminate the interferences in ECG waveform.

1. Electro static shielding:- Place a ground conducting plane between the source of the electric field and the measurement system.

2. Magnetic shield: Use high permeability materials.

3. Use twisted cables to reduce magnetic flux and loop area.

Electro static shielding:



Electrostatic shielding used to remove electric field interference on an electrocardiograph.

Isolation capacitor used to isolate patient from power line.

3.8 Right Leg driven ECG amplifier:

A Driven Right Leg Circuit or DRL circuit is an electric circuit that is often added to biological signal amplifiers to reduce Common-mode interference. Biological signal amplifiers such as ECG (Electrocardiogram) EEG (Electroencephalogram) or EMG circuits measure very small electrical signals emitted by the body, often as small as several micro-volts (millionths of a volt).

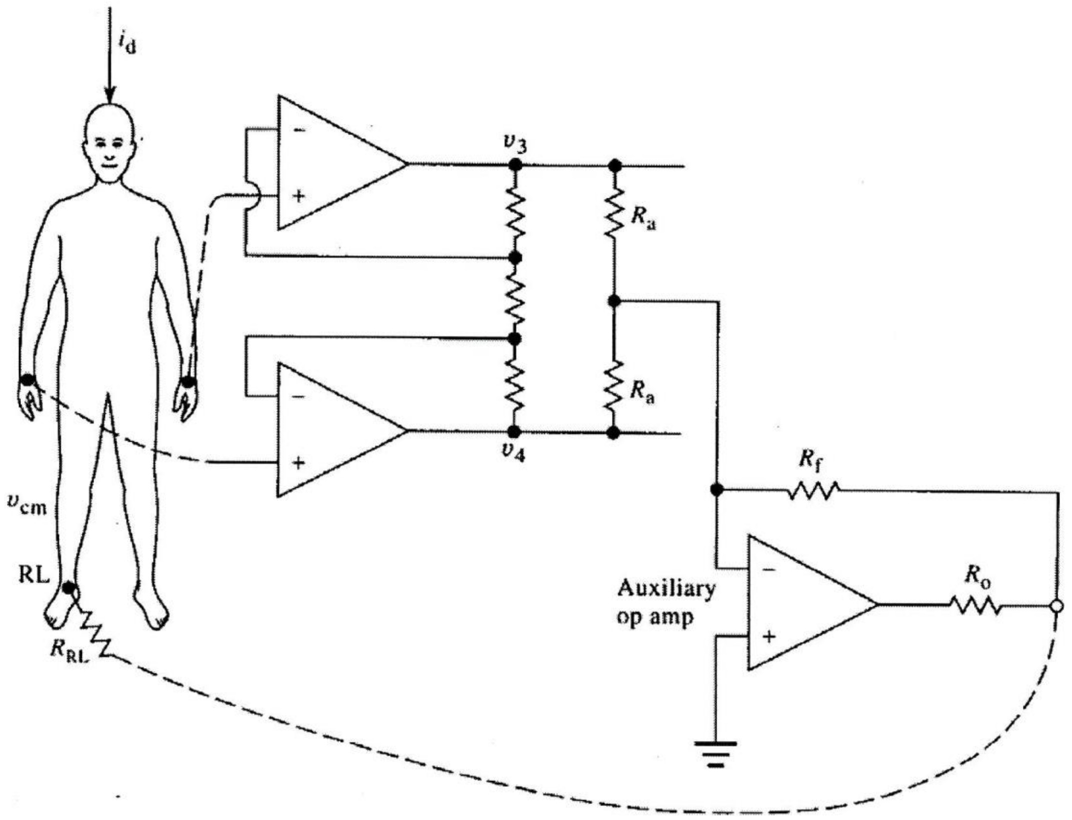
Unfortunately, the patient's body can also act as an antenna which picks up electromagnetic interference, especially 50/60 Hz noise from electrical power lines. This interference can obscure the biological signals, making them very hard to measure. Right Leg Driver circuitry is used to eliminate interference noise by actively cancelling the interference.

Objective:

- Reduce interference in amplifier
- Improve patient safety

Approach:

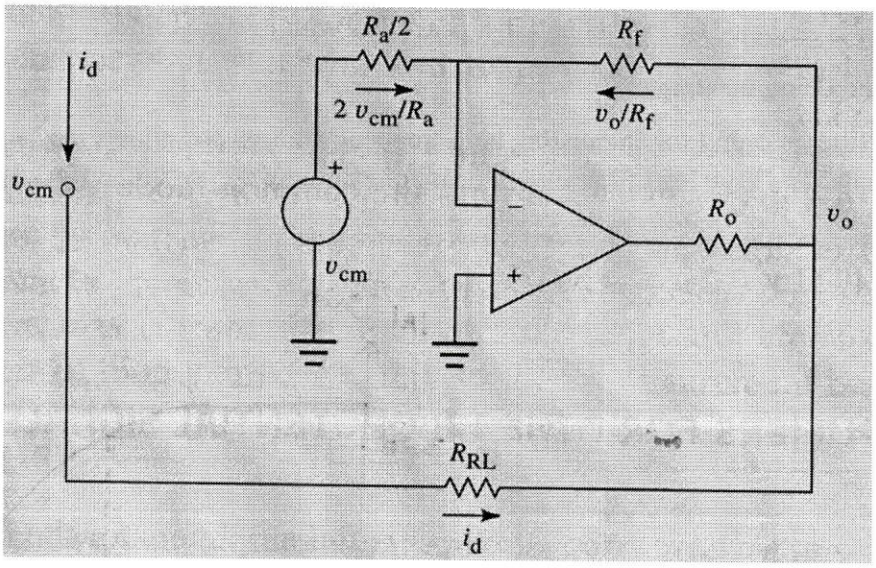
- Patient right leg tied to output of an auxiliary amp rather than ground.
- Common mode voltage on body sensed by averaging resistors, Ra's & R_F fed back to right leg.
- Provides negative feedback to reduce common mode voltage.
- If high voltage appears between patient and ground, auxiliary Op-amp effectively un-grounds the patient to stop current flow.



Determine the common-mode voltage Vcm on the patient in the driven right- leg circuit of when a displacement current id flows to the patient from the power lines.

Choose appropriate values for the resistances in the circuit so that the common-mode voltage is minimal and there is only a high-resistance path to ground when the auxiliary operational amplifier saturates.

Equivalent circuit to determine common mode gain,



KCL at point x

$$\frac{2v_{cm}}{R_a} + \frac{v_o}{R_f} = 0$$

i.e.

$$v_o = -\frac{2R_f}{R_a} v_{cm}$$

But

$$v_{cm} = R_{RL} i_d + v_o$$

Therefore

$$v_{cm} = \frac{R_{RL}}{1 + 2^{R_f}\!/_{R_a}} i_d$$

V_{cm} as small as possible choose large R_f and small Ra.

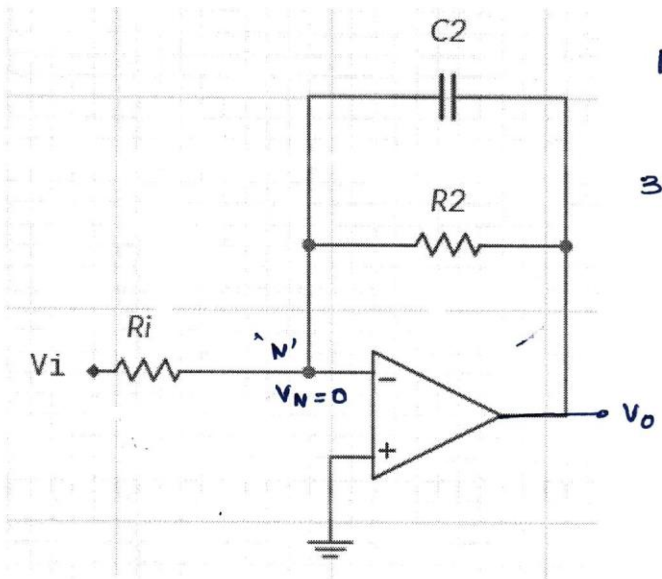
3.9 Band Pass Filter:

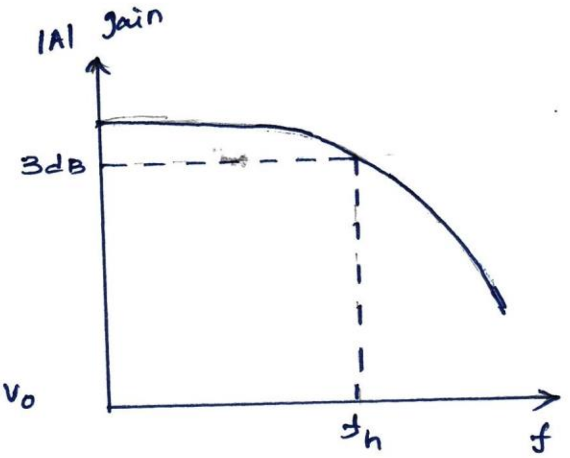
In general, the ECG signal is nature weak and only around 1mV amplitude. Therefore filter and amplifier circuits were designed into 3 stages with a total gain of 1000 to bring the signal to around 1V. Circuit designed included of instrumentation amplifier, bandpass filter and notch filter. The frequency bandwidth of ECG is between 0.05Hz until 100Hz.

Band pass filter is designed by cascading High pass filter with low pass filter.

Low pass Filter Using op-amp:

The Low pass filter is useful for attenuating high frequency noises and allows the low frequency signals. The Low Pass filter circuit using one op-amp shown in the fig 3.9(a).





Apply KCL at node 'N'

$$\frac{V_i}{R_i} = -\frac{V_o}{R_2 \parallel \frac{1}{j\omega C_2}}$$

$$\frac{V_i}{R_1} = -\frac{V_o}{\frac{R_2 \times 1/j\omega C_2}{R_2 + 1/j\omega C_2}}$$

$$\frac{V_i}{R_1} = -\frac{V_o}{\frac{R_2}{1+j\omega R_2 C_2}}$$

$$\frac{V_i}{R_1} = -\frac{V_o\,(1+j\omega R_2 C_2)}{R_2}$$

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}\,\frac{1}{1+j\omega R_2 C_2}$$

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}\,\frac{1}{1+j\omega \tau}$$

where $\tau = R_2 C_2$, time constant

Let $f_h = \frac{1}{2\pi R_2 C_2}$, $\omega = 2\pi f$

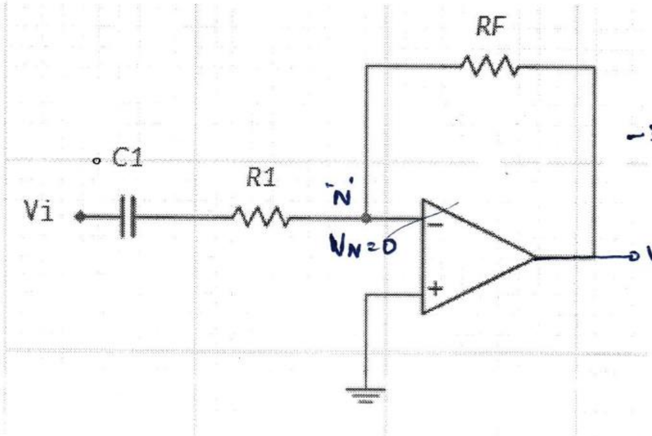
$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}\left(\frac{1}{1+j\,2\pi f R_2 C_2}\right)$$

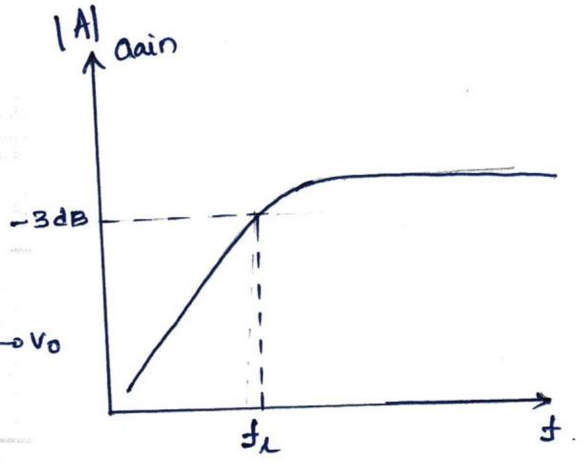
$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}\left(\frac{1}{1+j\,(f/f_h)}\right)$$

where $f_h \Rightarrow$ Higher cut off frequency of LPF.

High Pass filter:

High pass filter allows the higher frequencies which are above lower cut off frequency. Such a circuit is useful for amplifying a small ac voltage that rides on top of a large dc voltage,because Ci block dc.





$$\frac{V_i}{R_1 + 1/j\omega C_1} = -\frac{V_o}{R_F}$$

$$\frac{V_i}{\frac{1 + j\omega R_1 C_1}{j\omega C_1}} = -\frac{V_o}{R_F}$$

$$\frac{j\omega C_1}{1 + j\omega R_1 C_1} V_i = -\frac{V_o}{R_F}$$

$$\frac{V_o}{V_i} = -R_F \frac{j\omega C_1}{1 + j\omega R_1 C_1}$$

Multiply & divided by R_1

$$\frac{V_o}{V_i} = -\frac{R_F}{R_1} \frac{j\omega R_1 C_1}{1 + j\omega R_1 C_1}$$

where Time constant $\tau = R_1 C_1$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = A = -\frac{R_F}{R_1} \frac{j\omega\tau}{1 + j\omega\tau}$$

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

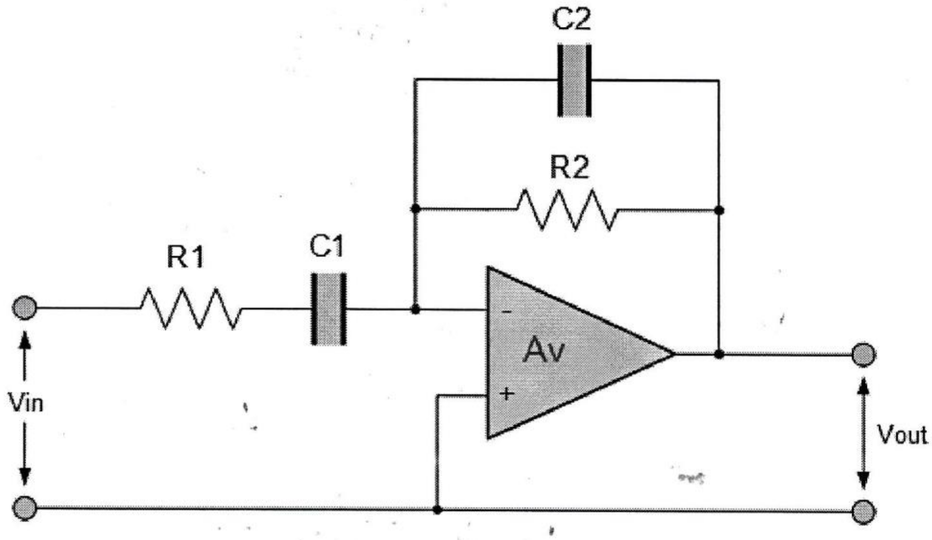
$$A = -\frac{R_F}{R_1} \frac{j\omega\tau}{1 + j\,2\pi f R_1 C_1}$$

$$A = -\frac{R_F}{R_1} \frac{j\omega\tau}{1 + j\,(f/f_L)}$$

where f_L is Lower cut off frequency of HPF.

Band pass filter:

Cascading of High pass filter followed by Low pass filter results in a band pass filter. Band pass filter which amplifies frequencies over a desired range and attenuates higher and lower frequencies. But this configuration having two op-amp. The band pass filter is designed by one op amp is given in the fig.



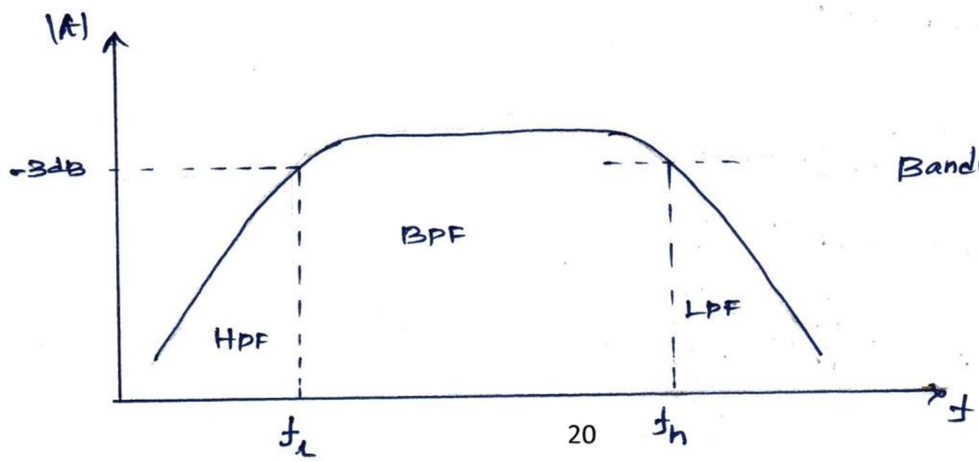
Band pass Filter is the cascading of HPF and LPF.

So, the frequency response of BPF.

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{R_2}{R_1}\,\frac{j\omega\tau}{1+j2\pi f R_1C_1}\cdot -\frac{R_2}{R_1}\,\frac{1}{1+j2\pi f R_2C_2}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = \left(\frac{R_2}{R_1}\right)^2 \frac{j\omega\tau}{(1+j2\pi f R_1C_1)(1+j2\pi f R_2C_2)}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = \left(\frac{R_2}{R_1}\right)^2 \frac{j\omega\tau}{(1+j\,f/f_L)(1+j\,f/f_h)}$$



Bandwidth = $f_h - f_L$