Operational Amplifier Filters

Operational amplifiers

Device with high input impedance, low output impedance, high gain, high bandwidth, low power consumption, low output power etc.

Open loop gain very high. Gain can be controlled by negative feed back and this increases the utility. Used in inverting and noninverting mode. Inverting mode - input impedance low. Noninverting mode -input impedance very high. Output cannot exceed the saturation voltage.

Two golden rules (Inverting mode):

Golden rule 1 : opamp will work in such a way that it will drives the two inputs to same level

Golden rule 2 : No current can flow into opamp

Comparators

A comparator compares a signal voltage on one input with a known voltage called reference voltage on the other input.

In the simplest form it is opamp working in open loop mode, having +ve or -ve saturation voltage as output. Used in digital circuits, Schimitt triggers, voltage level detectors and oscillators.

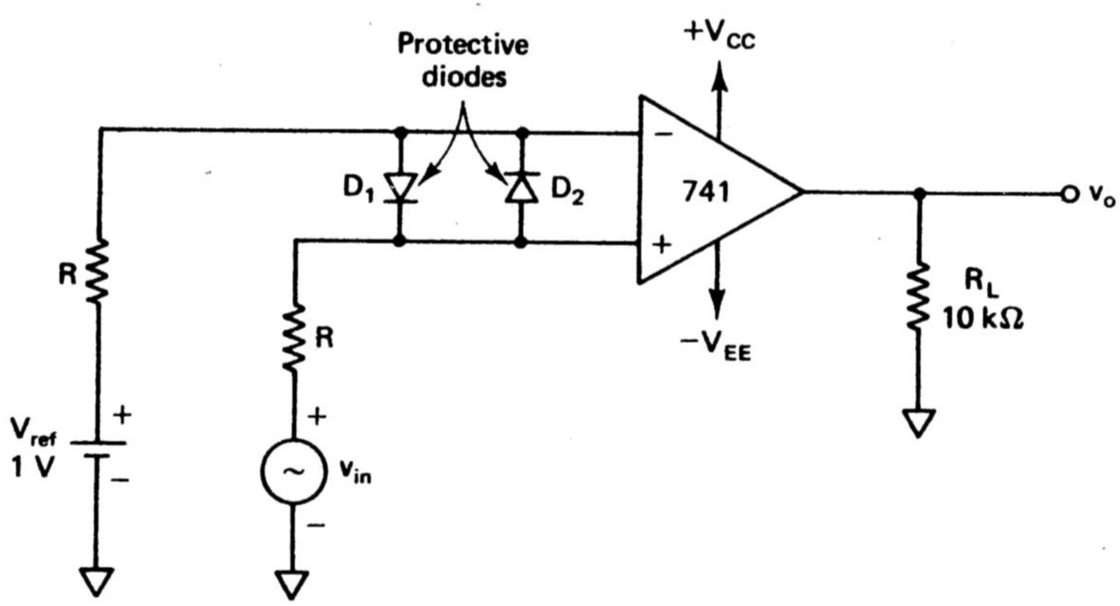
Basic Comparator

V_{ref} = 1 V at inverting terminal and inp signal at noninverting terminal

when $V_{in} < V_{ref}$; $v_o = -V_{sat}$ Similarly, when $V_{in} > V_{ref}$; $v_o = +V_{sat}$

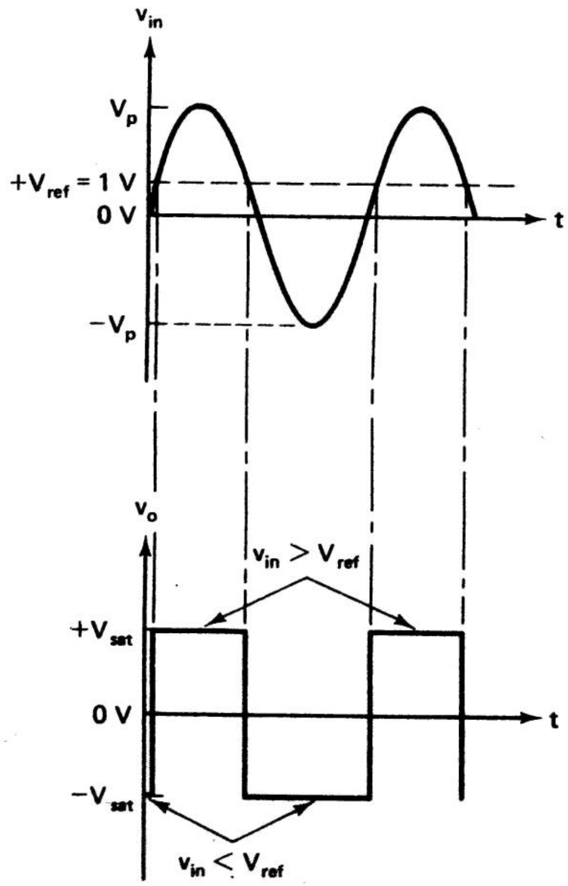
Output will swing between $+V_{sat}$ and $-V_{sat}$ It is working as Voltage level detector. It is working like a digital switch, on when input voltage is high compared to reference voltage and off when input voltage is low compared to in put voltage.

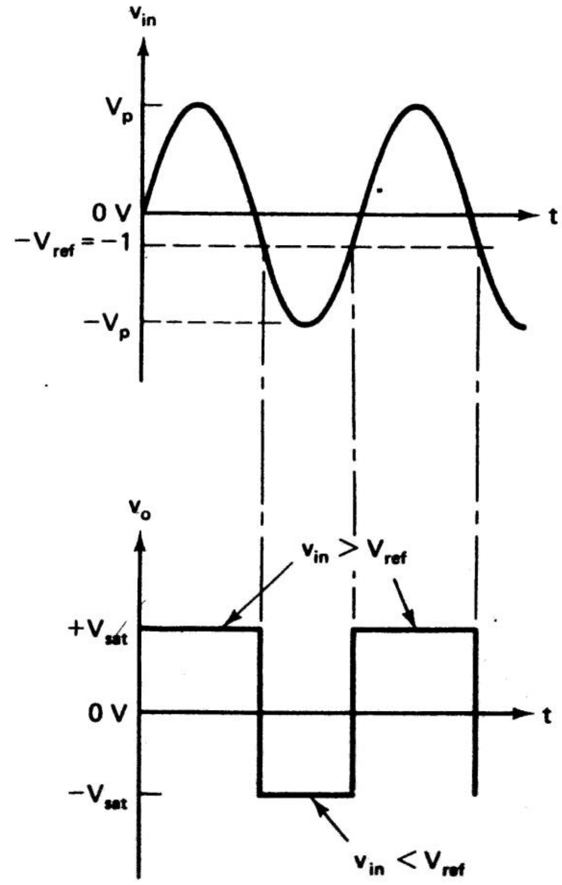
Diodes protect from high input voltage. v_{id} is clamped between +0.7 V to -0.7 V



Comparators

Note V_{ref} and output wave form. Wave form width is dependent on the reference voltage. Non-inverting comparator: Input and output in same phase. V_{ref} to inverting terminal: polarity changes



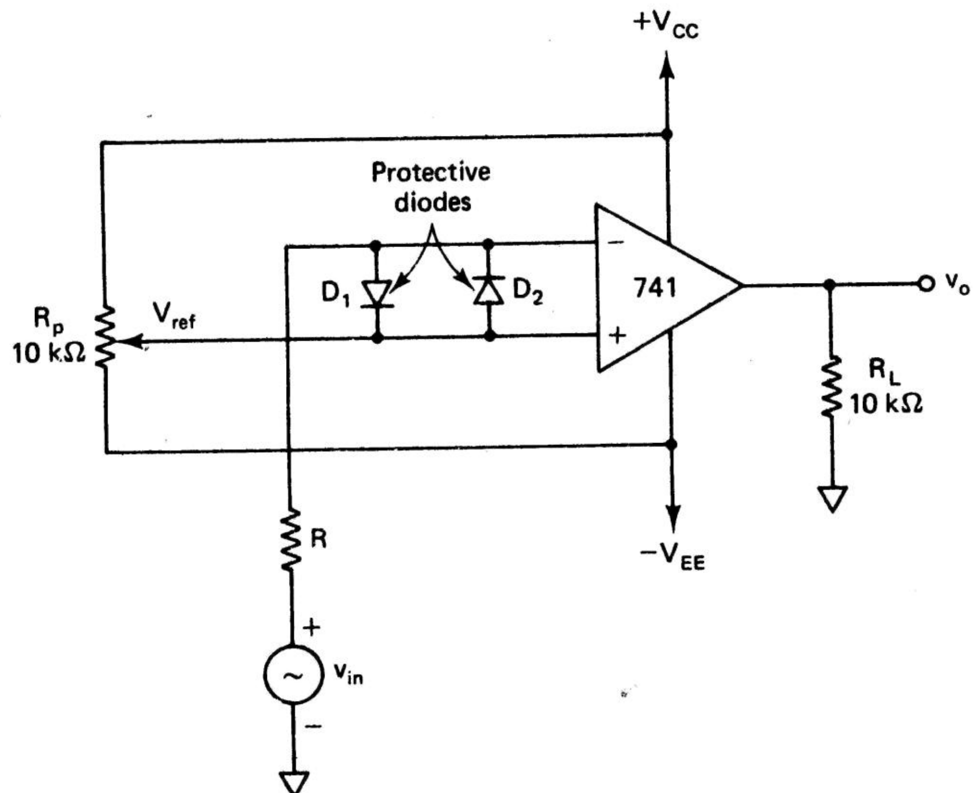


Comparators

Input to inverting terminal, it will behave opposite of previous example.

when $V_{in} > V_{ref}$; $v_o = - V_{sat}$ Similarly, when $V_{in} < V_{ref}$; $v_o = + V_{sat}$

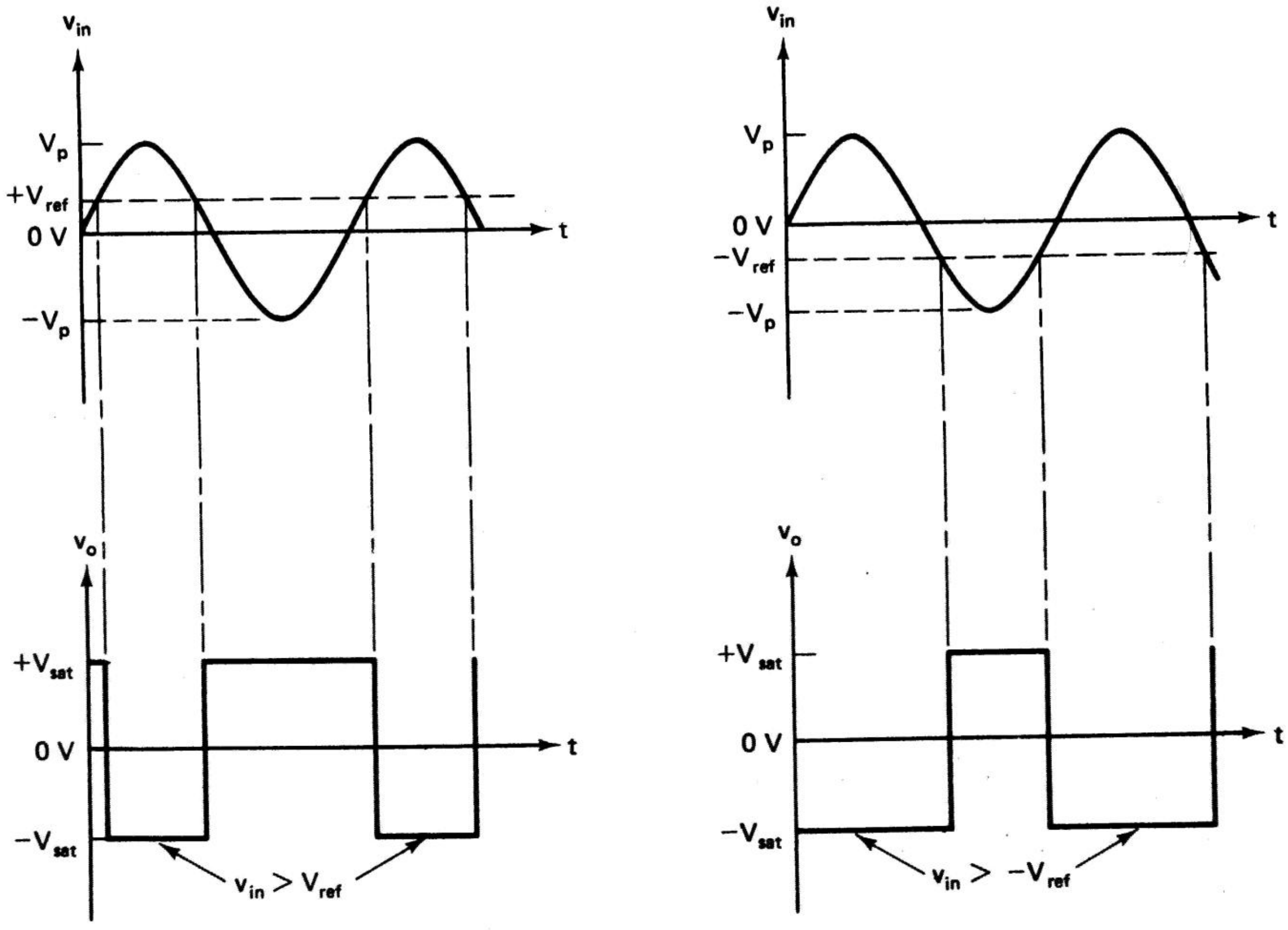
Potentiometer to change the V_{ref}



(a)

Comparators

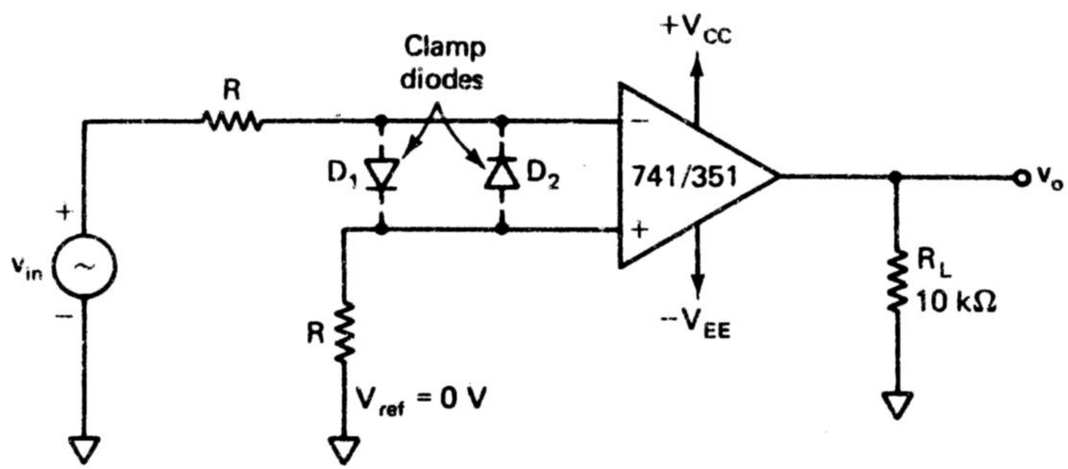
Output waveform is 180^0 out of phase with the previous example output for the same input. Rising signal is falling edge and similarly falling signal is rising edge. Time period of the wave form is same as sinusoidal waveform. On time and Off time depends on V_{ref}



Zero detector Comparators

Zero detector

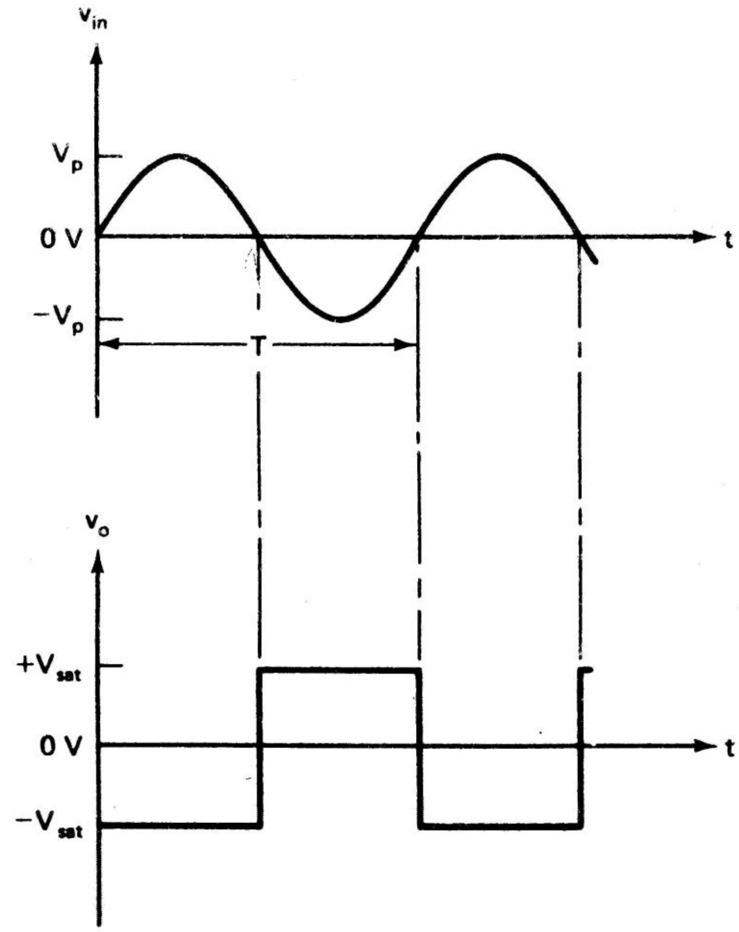
When reference voltage is zero, the output will swing whenever input signal crosses zero. The output will be square wave for a sinusoidal waveform.



(a)

Comparators

Conversion of sinusoidal waveform in to square waveform. Falling edge can be made rising edge by changing the input terminal



(b)

Regenerative Comparators

Schmitt trigger - Regenerative comparator

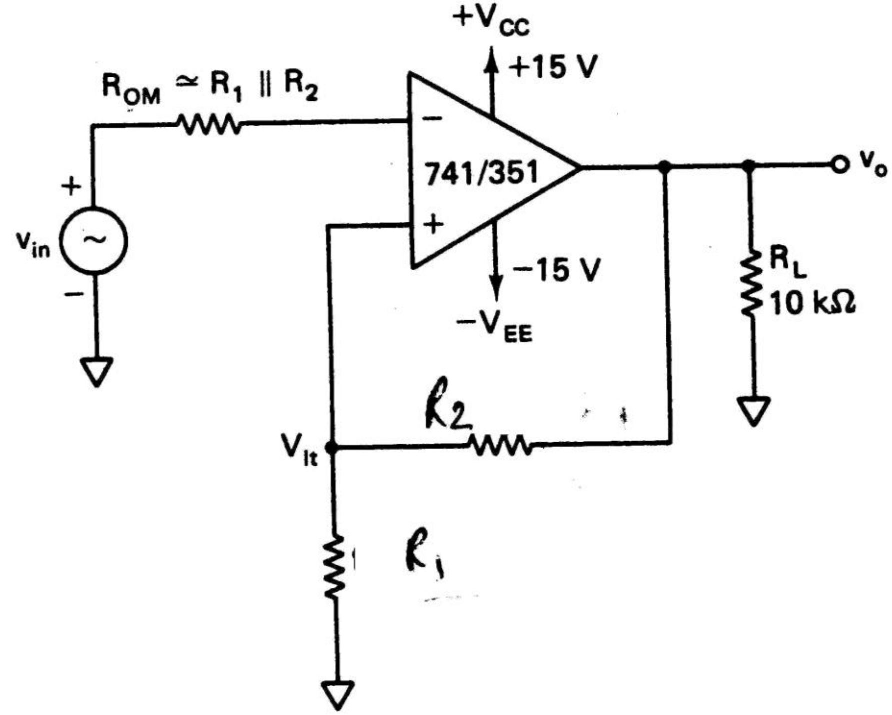
This is a inverter comparator with positive feed back. The reference voltage at non-inverting terminal depends on the magnitude and polarity of output voltage. It is divided between R1 and R2.

V_{ut} = Upper threshold, when V_o is +ve

V_{lt} = Lower threshold, when V_o is -ve

$$V_{ut} = \frac{R_1}{R_1 + R_2}(+V_{sat})$$

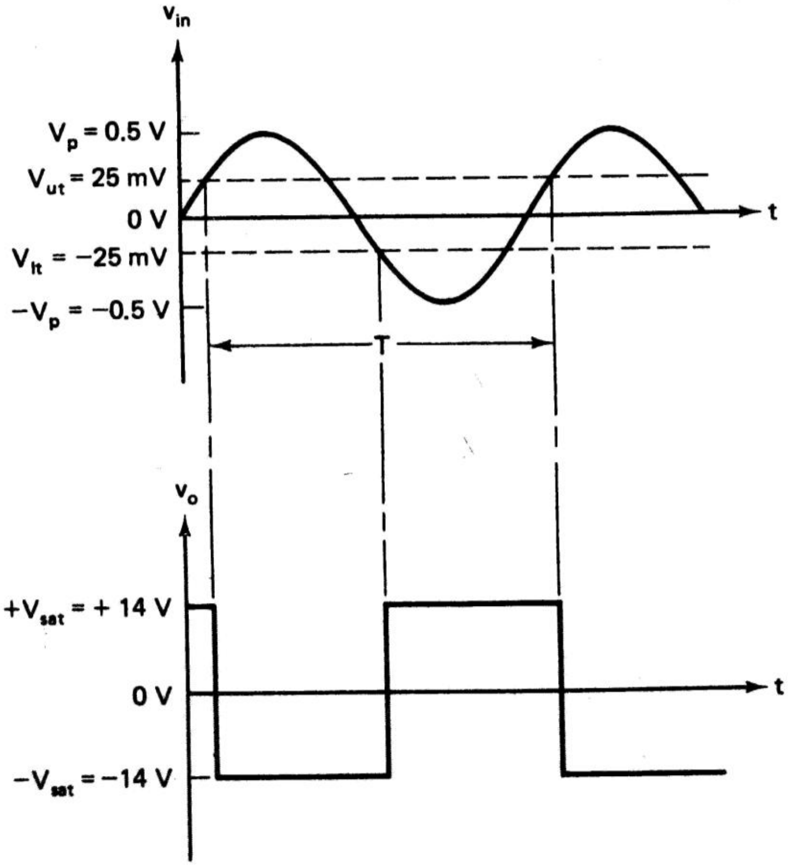
$$V_{lt} = \frac{R_1}{R_1 + R_2}(-V_{sat})$$

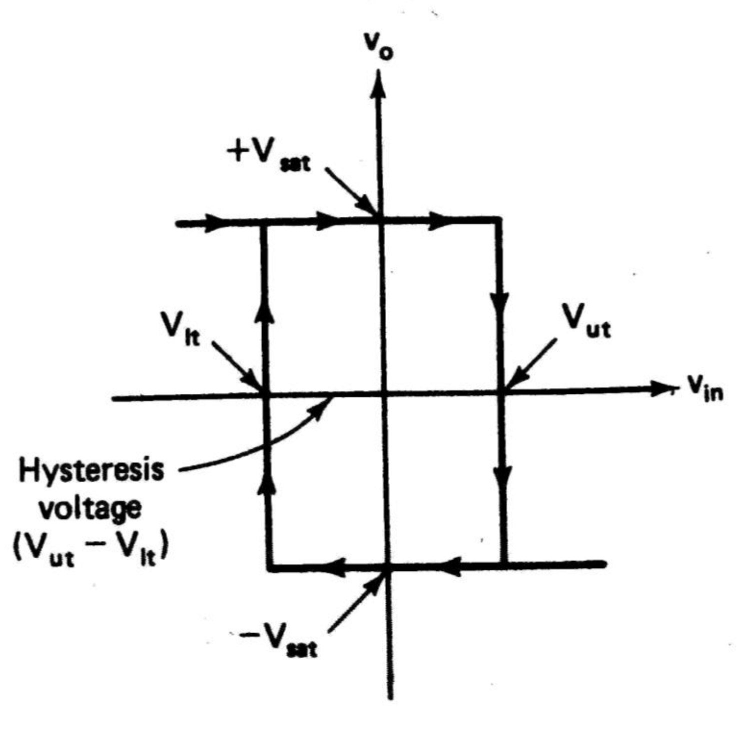


Comparators

Regenerative effect will make switching action faster, limited by slew rate.

Upper threshold and lower threshold can be fixed to make the circuit noise immune, this is also known as dead zone. It is sort of hysteresis. When input signal voltage is between V_{ut} and V_{lt} it will not change the output.





Voltage limiter

Voltage limiter circuit is added in the comparator circuit to limit the output voltage. Limiter circuit can be made with the combination of diodes, zener

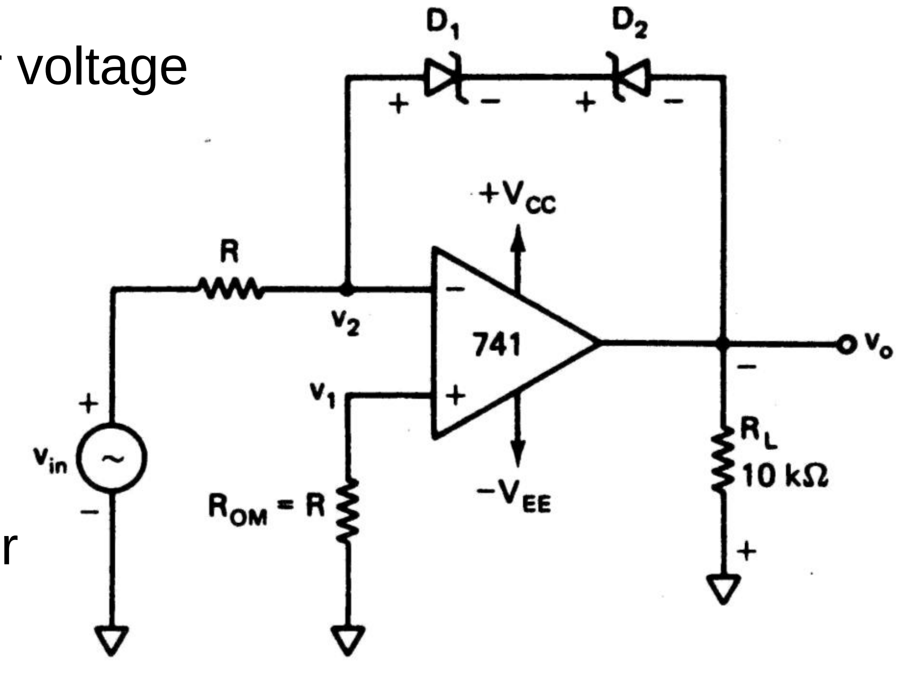
Zener diode - forward biased (~ 0.7 V silicon), reverse bias (Zener voltage)

When V_2 = +ve, V_o = -ve,

D_1 is forward biased and D_2 is reverse biased

$V_o = V_{D1} + V_Z$;

V_{D1} = Diode forward voltage, V_Z = Zener voltage



When V_2 = -ve, V_o = +ve,

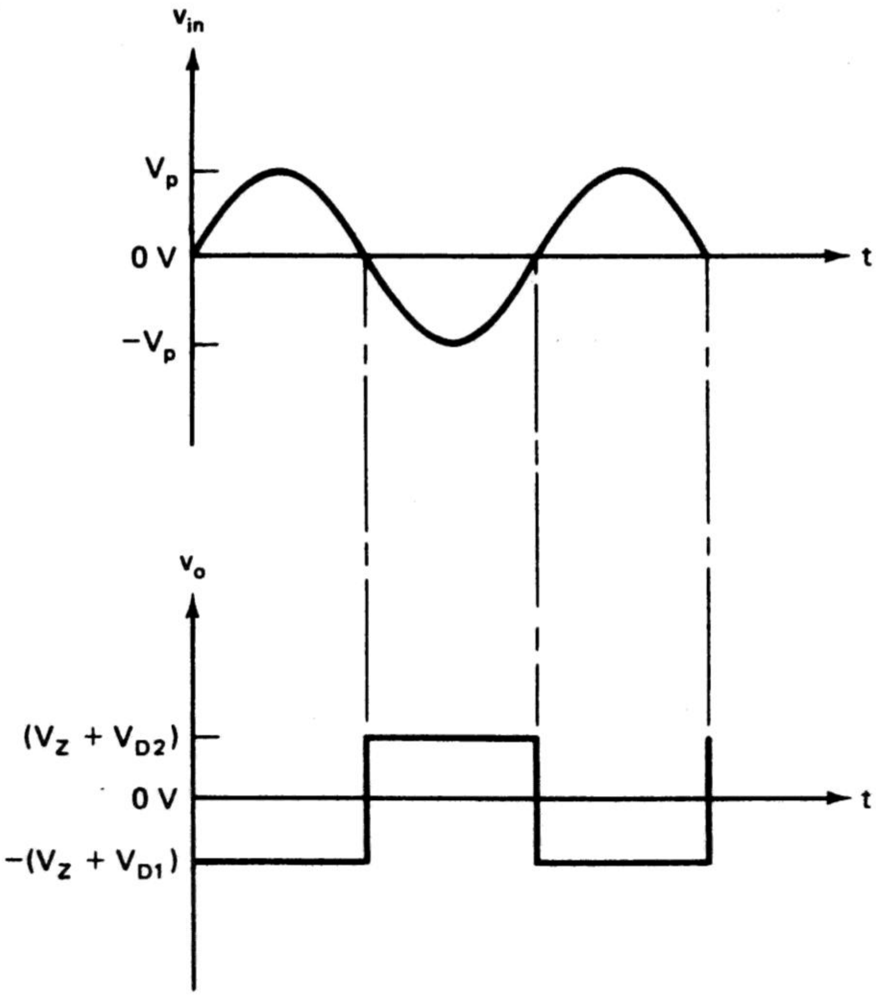
D_2 is forward biased and D_1 is reverse biased

$V_o = V_{D2} + V_Z$;

V_{D2} = Diode forward voltage, V_Z = Zener voltage

Voltage limiter

Sinusoidal waveform will be a square wave with voltage limiter. Diode and zener will conduct whenever voltage changes sign.



Upper voltage limit (V_{D1} + V_Z);

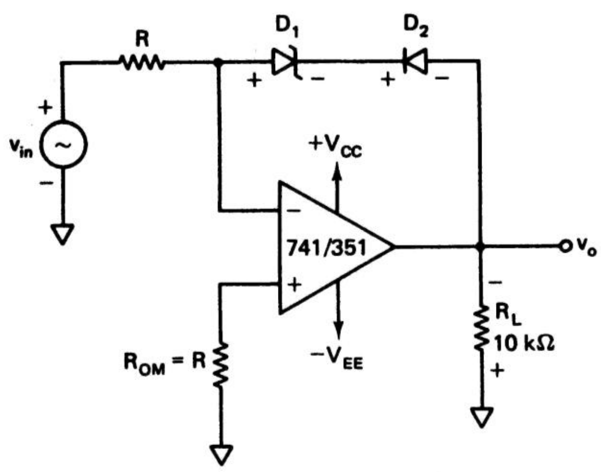
Lower voltage limit -(V_{D1} + V_Z)

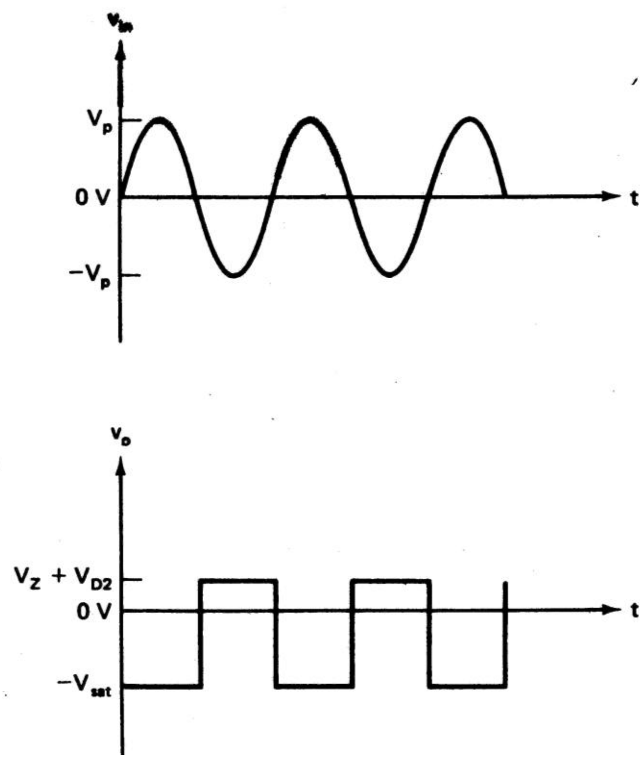
Voltage limiter

When the output is to be limited to one side, zener and diode can be used. The output is limited to (V_{D2} + V_Z) and -V_{sat}; D2 is forward biased when V_o is positive and the circuit works in negative feedback mode. D2 is reverse biased when V_o is negative and the circuit works in open loop mode.

When position of diode and zener is interchanged. Output waveform is unchanged.

During positive part of the waveform opamp is in open loop mode and during negative half it is in negative feedback mode.

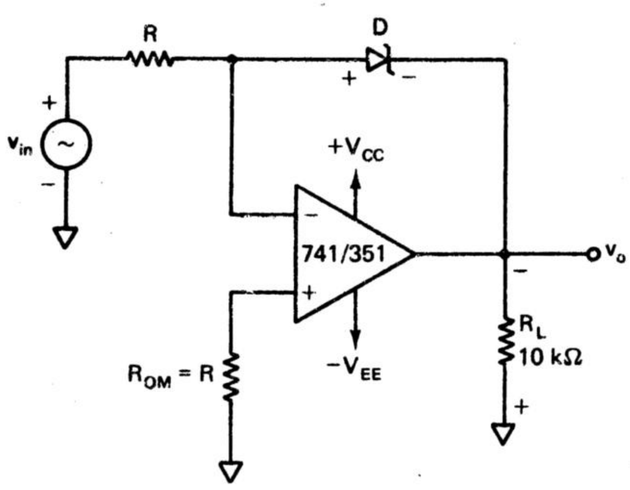




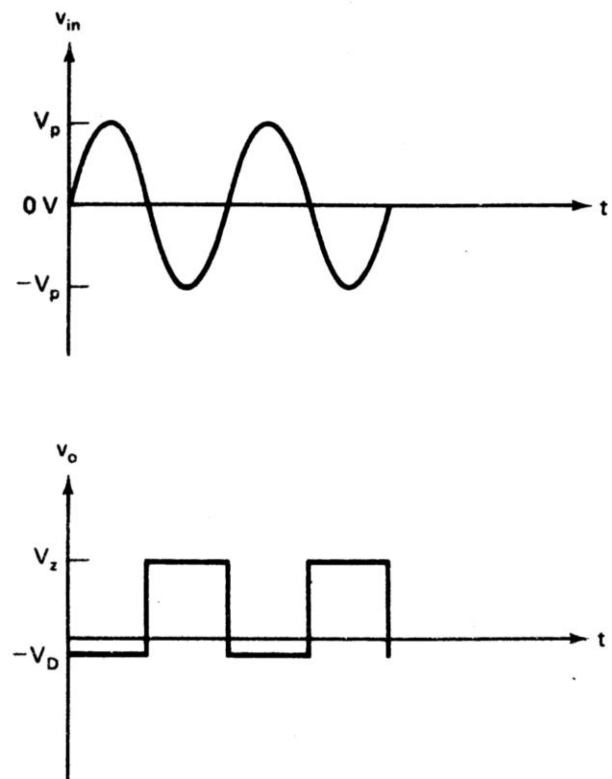
Voltage limiter

If only one zener is used: Output will vary between V_z and $-V_D$ Where V_Z is zener voltage and V_D is zener forward bias voltage. During positive part of the waveform zener is forward biased. During negative part of the waveform it is reverse bais and hence zener voltage.

If the zener direction is changed output will be $-V_z$ and V_D



(a)

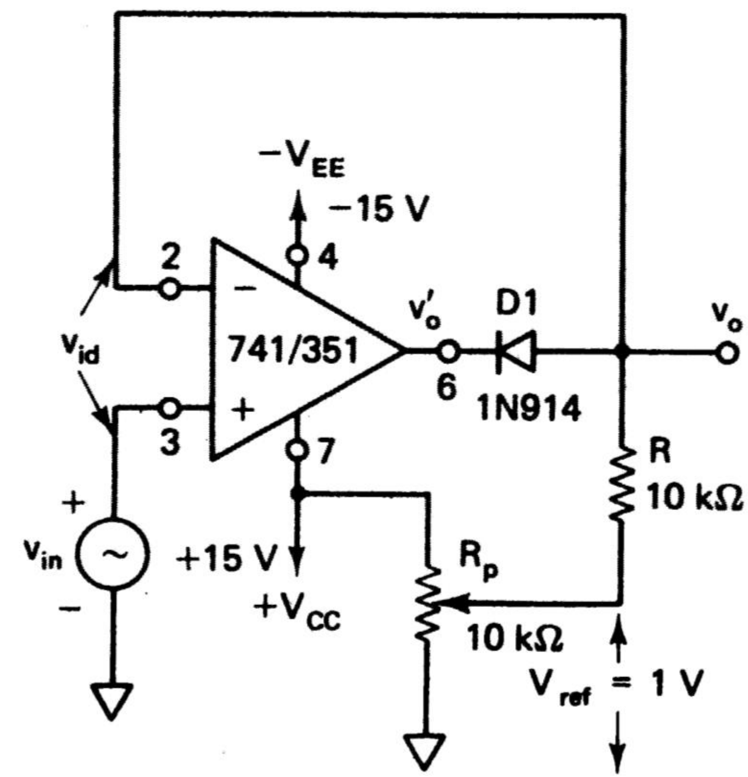


Clippers

Circuit which can remove (clip) some part of the input signal

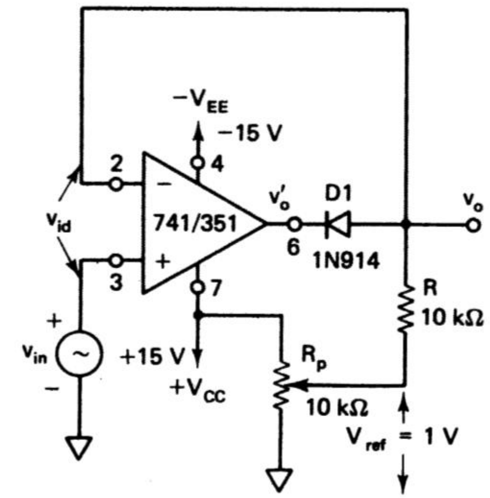
V_{ref} or the clipping voltage is set by potentiometer R_p, this also the biasing offset for diode. The diode will conduct whenever V_o' is less compared to V_{ref}

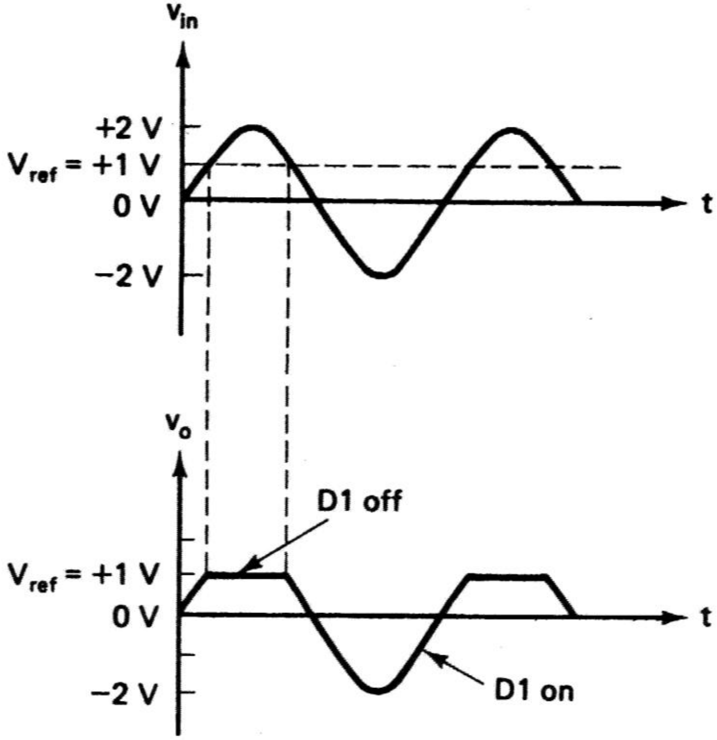
During diode on position, it works as a voltage follower, and in off position as open loop configuration. The voltage difference at input terminal is equal to voltage drop across diode divided by open loop gain of opamp, when it is on.

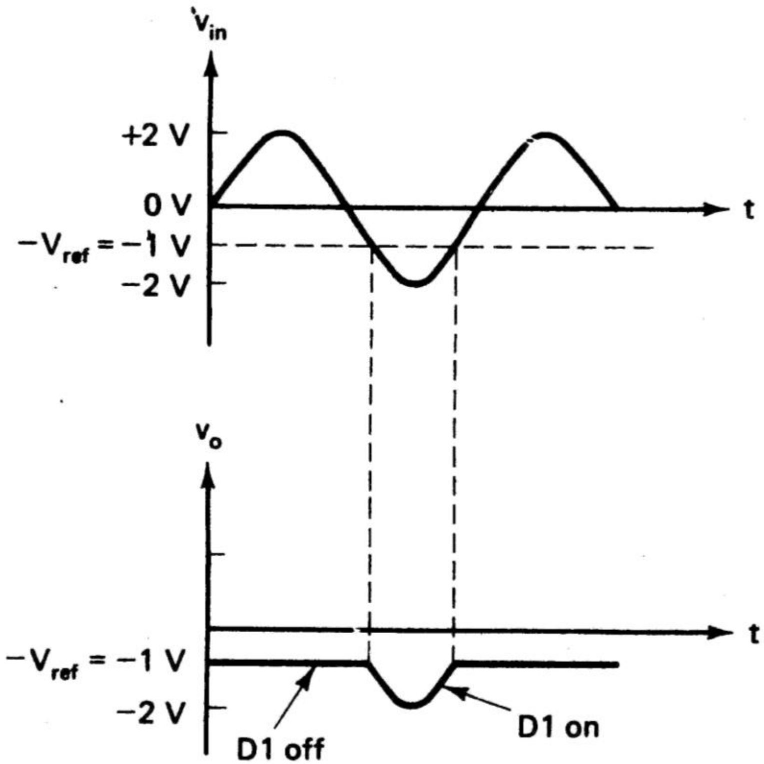


Clippers

When V_{in} is negative compared to V_{ref} Diode is forward biased and circuit is in voltage follower mode, output follows input. When V_{in} is positive compared to V_{ref} Diode is off and output is V_{ref} . Upper limit on V_{ref} is V_{sat} It is a positive clipper circuit

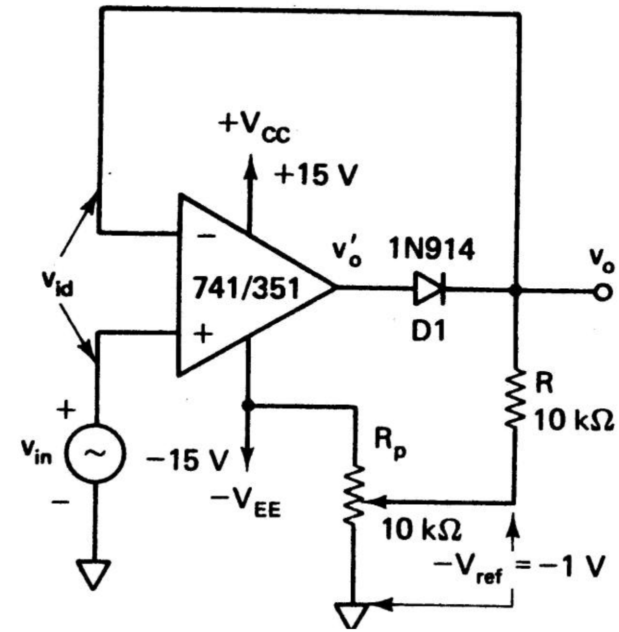


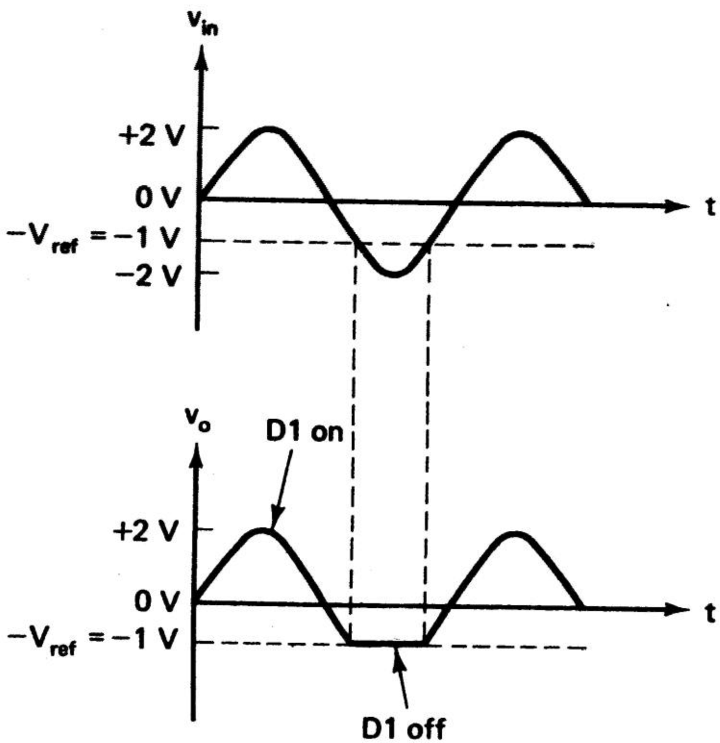


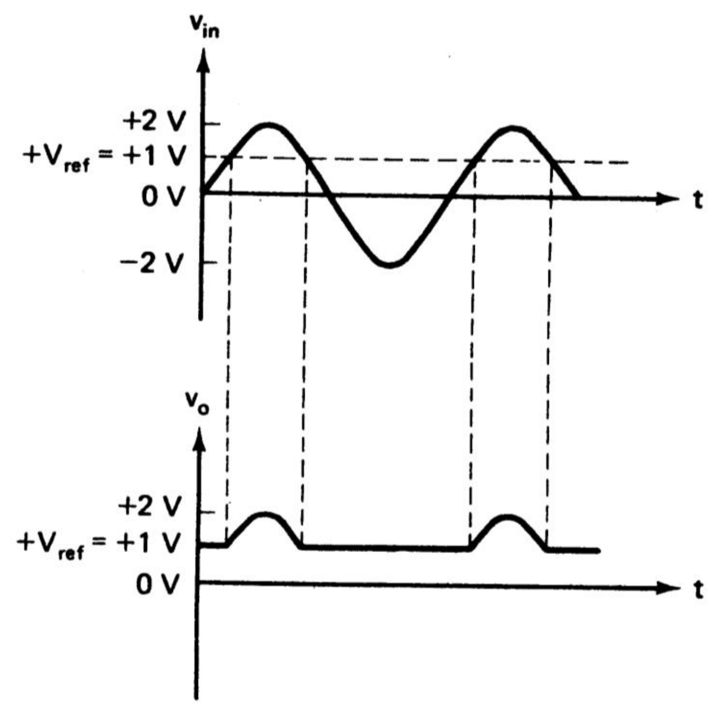


Clippers

When the direction of diode is changed, biasing direction also changes and the circuit behaves reverse of earlier circuit. Diode will be forward biased when V_{in} is higher compared to V_{ref}. Voltage below V_{ref} is clipped. It is a negative clipper circuit

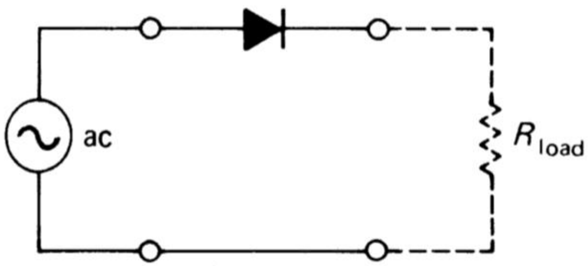


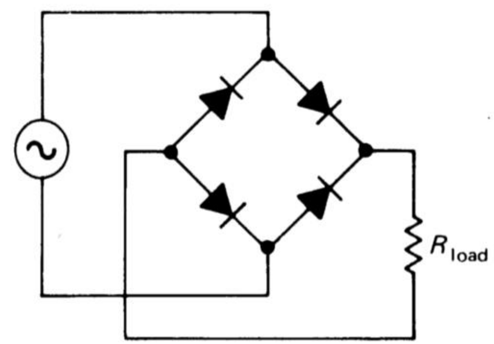


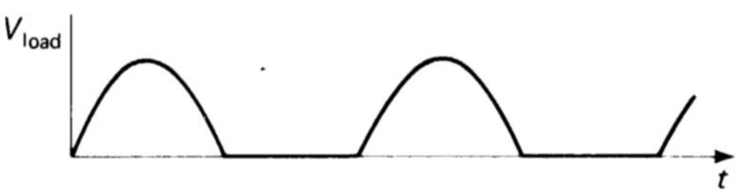


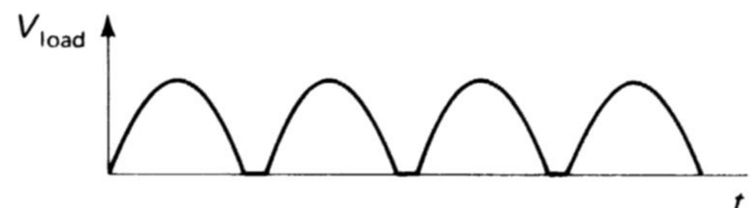
Half wave rectifier

Diodes when used as rectifier in power supplies, Voltage drop of 0.7 volt (silicon) or 0.3 volt (germanium) will occur (cut-in voltage). Input voltage should be > cut-in voltage to perform rectification. Gap between two halves is due to cut-in voltage.



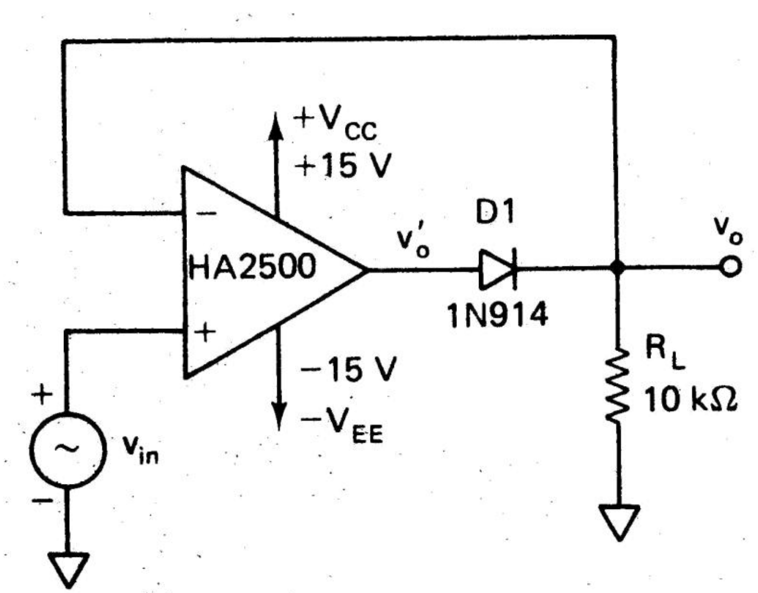


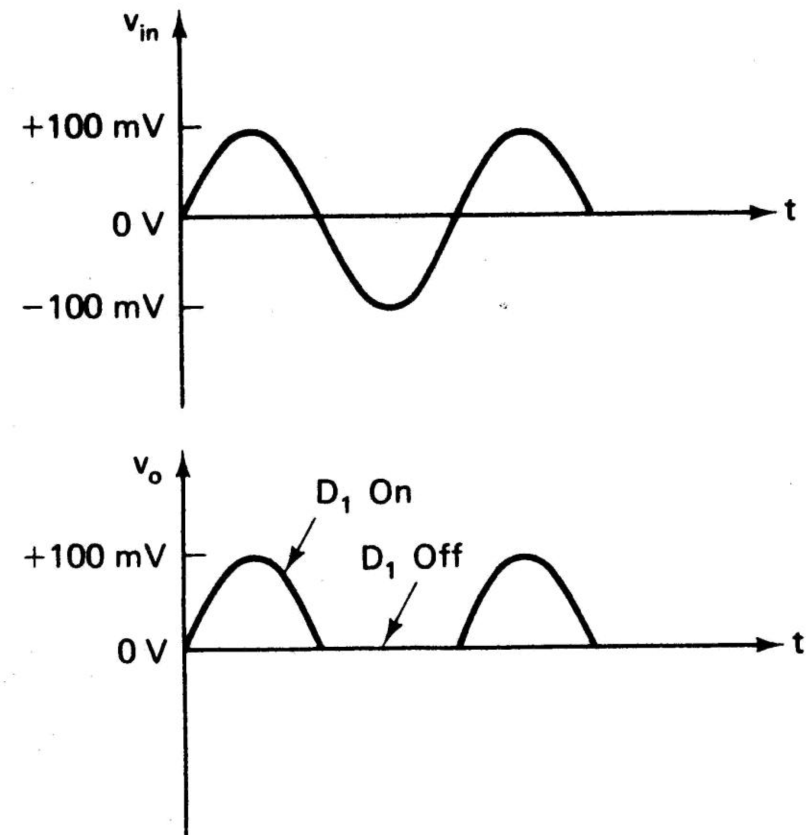




Half wave rectifier

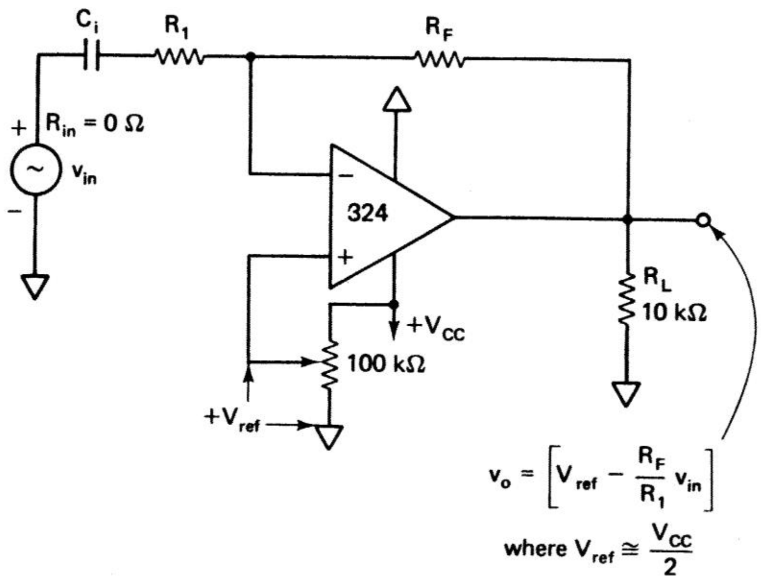
This is also a positive clipper with reference voltage as zero. When the input is above zero volt, diode is switched on and the voltage follower path is on. Advantage of such circuit is that it can rectify signal of milivolt level. Not possible with conventional diode circuit.

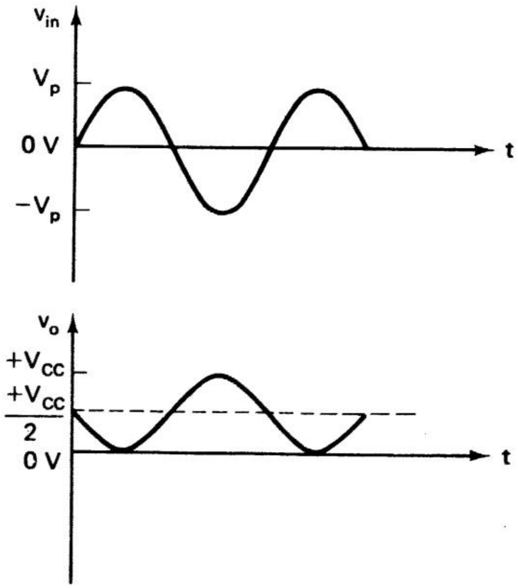




Clamper

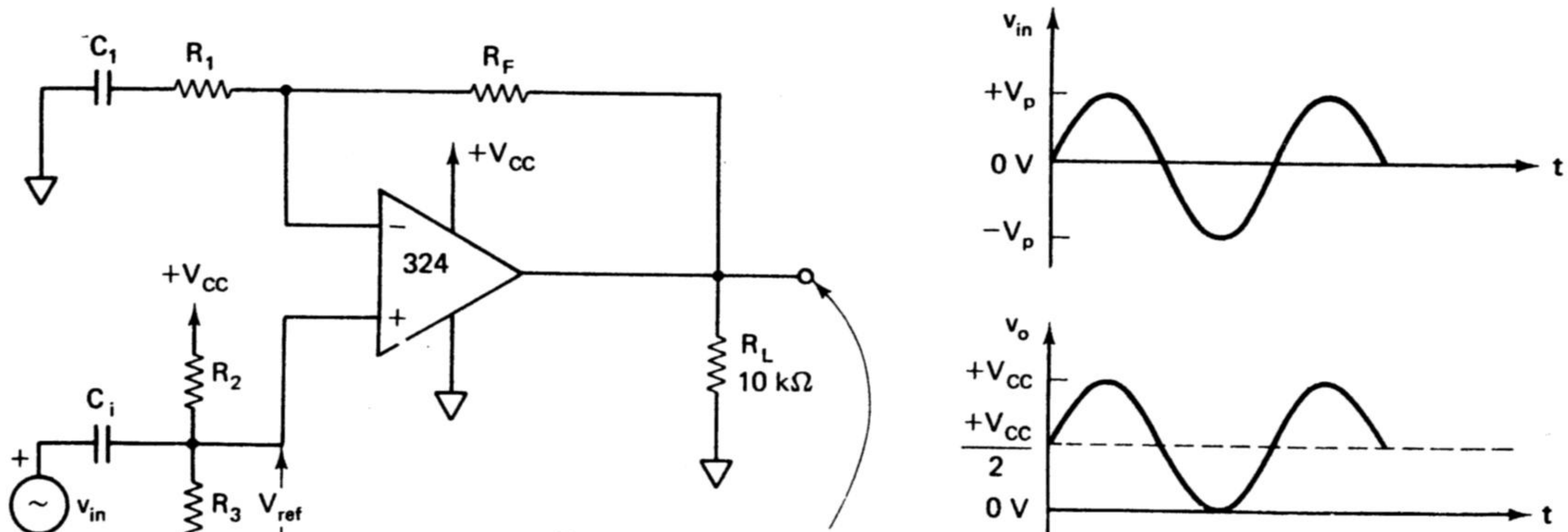
Shifting of the output in positive or negative direction. Can be used to convert bipolar signal to unipolar. For single supply opamp output can be only between ground & V_{sat}. When input signal is zero, voltage at noninverting terminal is V_{ref} and also at output. No current can flow through capacitor (DC signal). Output will change with this reference. This is a inverting clamper (input at inverting terminal).





Clamper

When the input is at noninverting terminal it is called as noninverting clamper. Capacitor are connected at ground terminal and input terminal. Ground terminal capacitor to maintain V_{ref} at output and at input to pass only AC component.



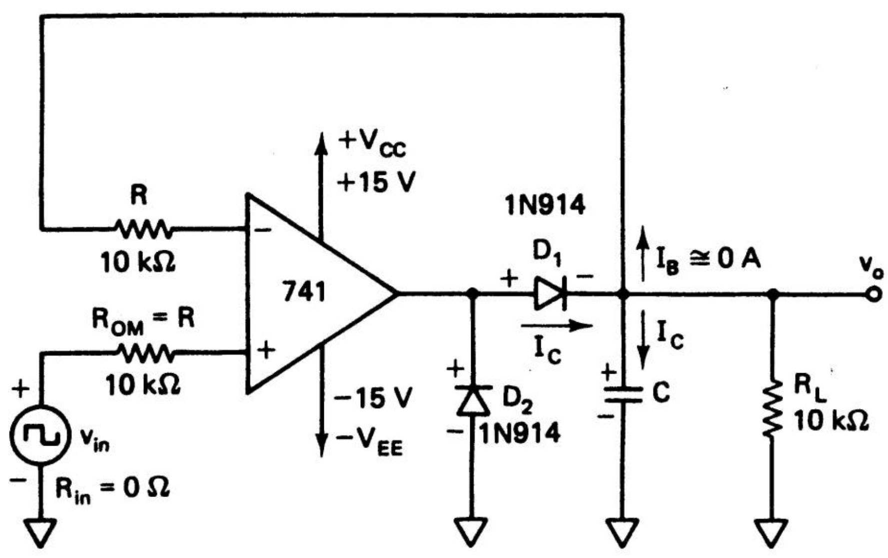
$$v_o = \left[V_{ref} + \left(1 + \frac{R_F}{R_1}\right)v_{in}\right]$$

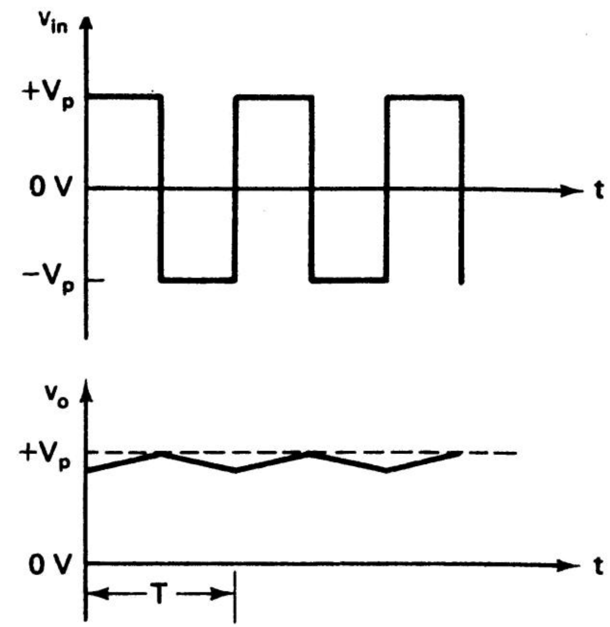
where $V_{ref} \cong \frac{V_{CC}}{2}$

Peak detector

It is voltage follower circuit, when output is positive, diode D_1 conducts and capacitor is charged to peak voltage. When output is negative, diode D_2 conducts or opamp output is grounded. Following relations to be maintained for satisfactory operation

For charging $CR_d < \frac{T}{10}$ For discharging $CR_L < 10T$





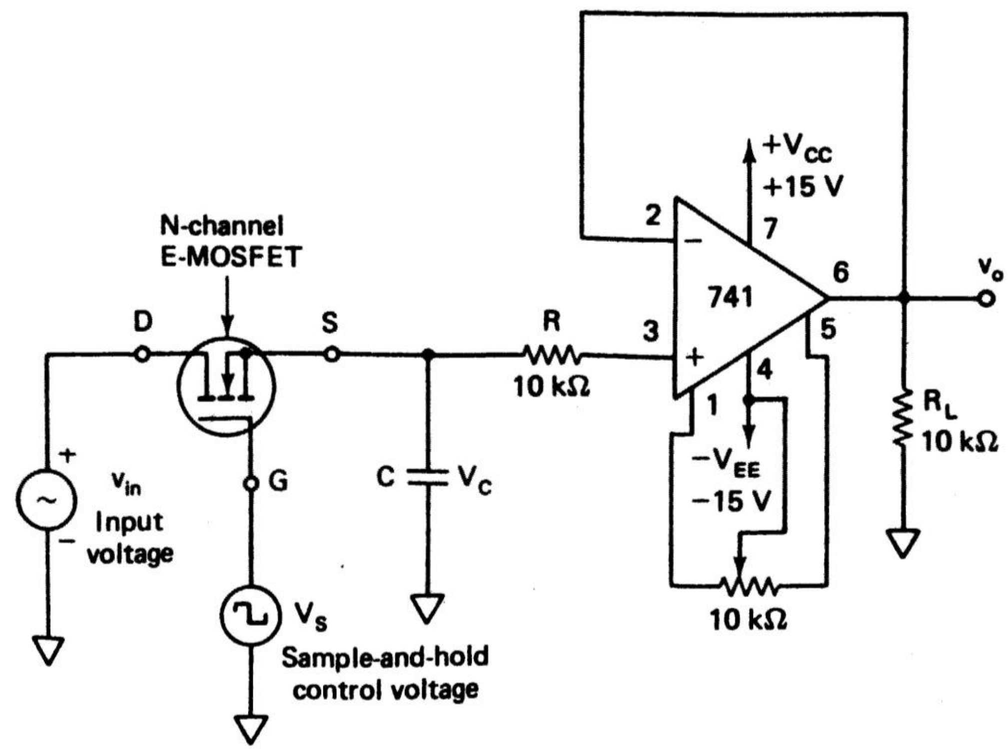
Sample and hold circuit

Sample and hold circuit, samples an input signal and hold the last value till it is sampled again.

Opamp is used in voltage follower mode, MOSFET is used as switch

Capacitor is charged to input voltage when MOSFET is on.

Capacitor holds the value when MOSFET is off. Highly dependent on the quality of capacitor.

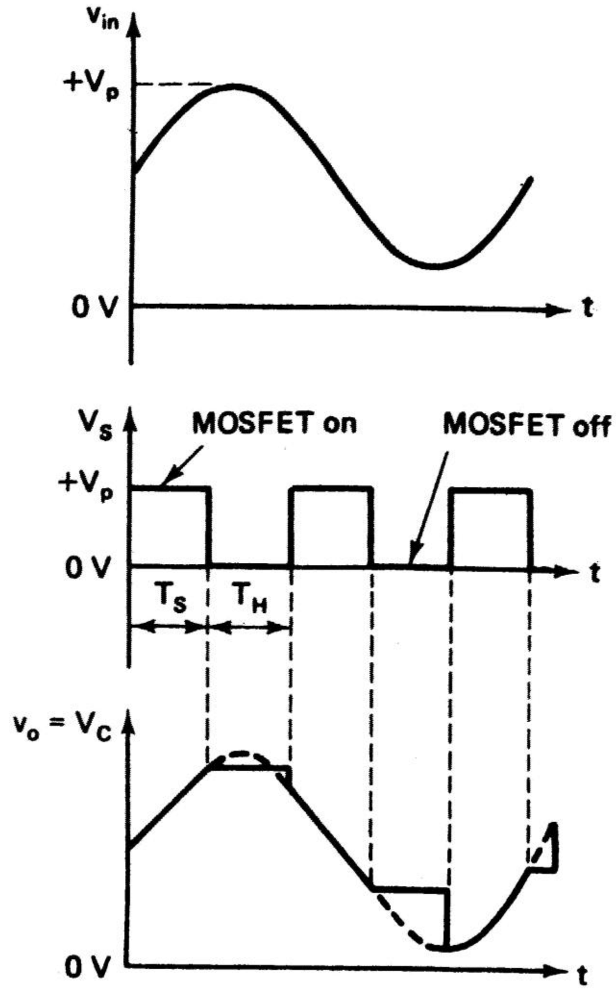


Sample and hold circuit

T_S is sample time

T_H is hold time, during this output of opamp will hold voltage

During hold time the capacitor can discharge through opamp but input resistance very high for voltage follower. Generally output is processed during hold position. Better waveform at output can be obtained by higher sampling frequency. Precision capacitor should be used (very low leakage).



(b)

Filters

Electronics circuits having property of passing the desirable signal frequencies and rejecting the undesirable signal frequencies. This is possible by using RC, RL and RCL networks.

Filters classification:

- Analog or digital
- Passive filters- uses passive components, no external power is required to drive
- Active filters- uses active components, requires external power
- Audio frequency (AF) or Radio Frequency (RF)

Filters

Low pass filter - constant gain from 0 Hz to high cut off frequency

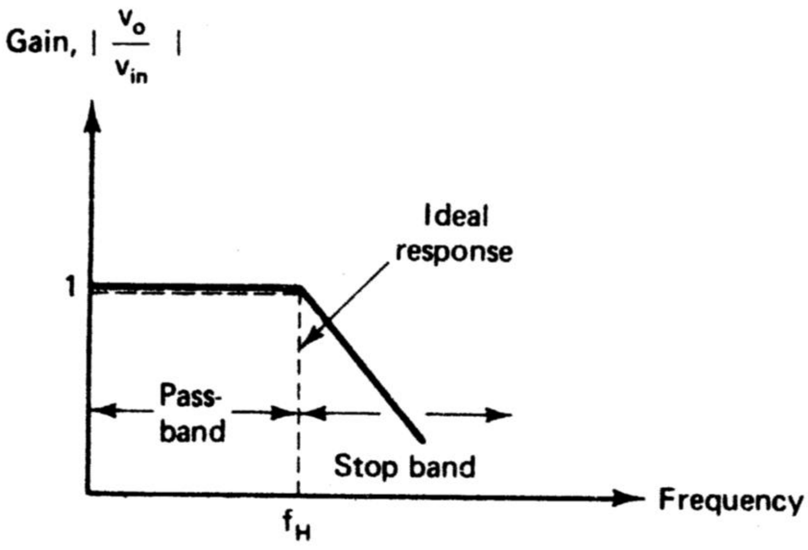
Pass band 0 - f_H and cut-off band > f_H

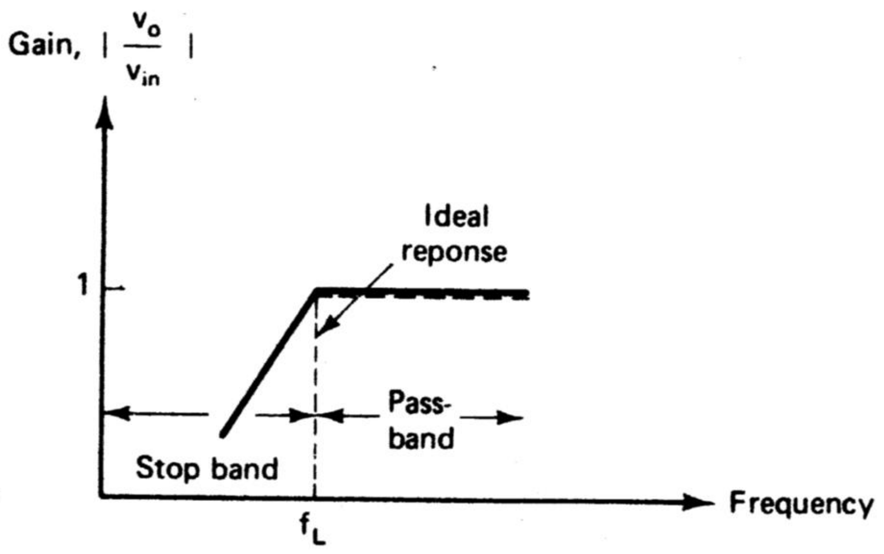
High pass filter - constant gain from cutoff frequency to infinite

Cut-off band 0 - f_L and pass band > f_L

Ideally, Cut-off band gain = 0

Discontinuities not possible in actual circuits, practical filter circuits will have roll off characteristics





Filters

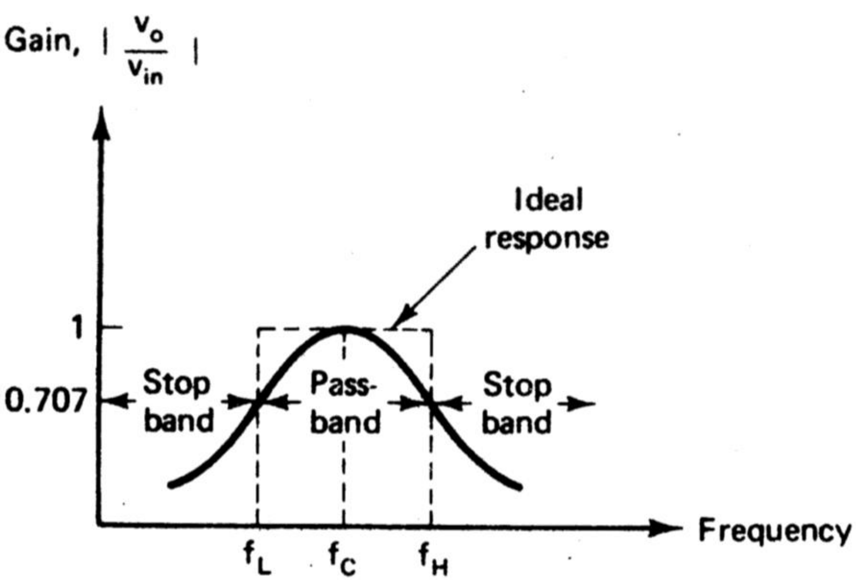
Band pass filter - passes a band of frequencies

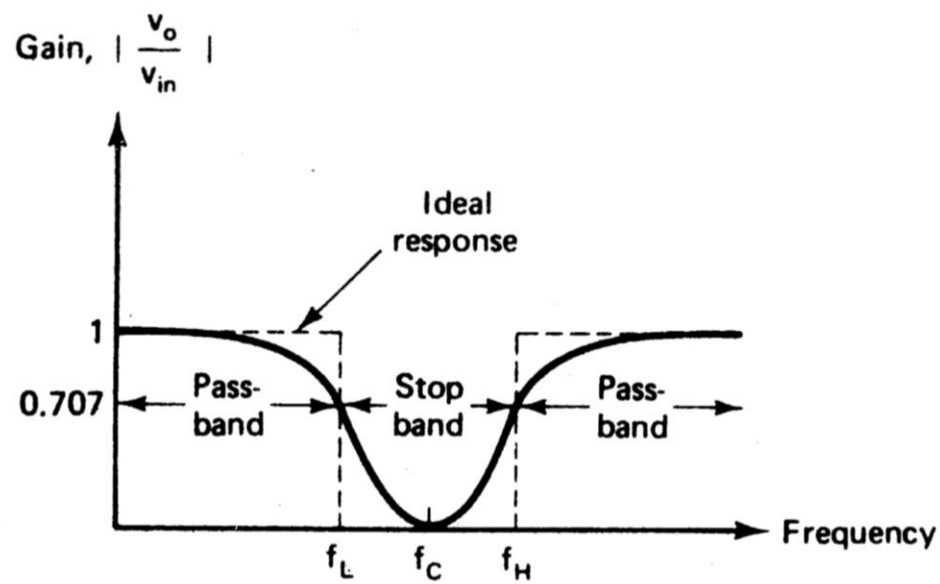
Pass band $f_L > f < f_H$

Band reject filter - rejects a band of frequencies

Reject band $f_L > f < f_H$

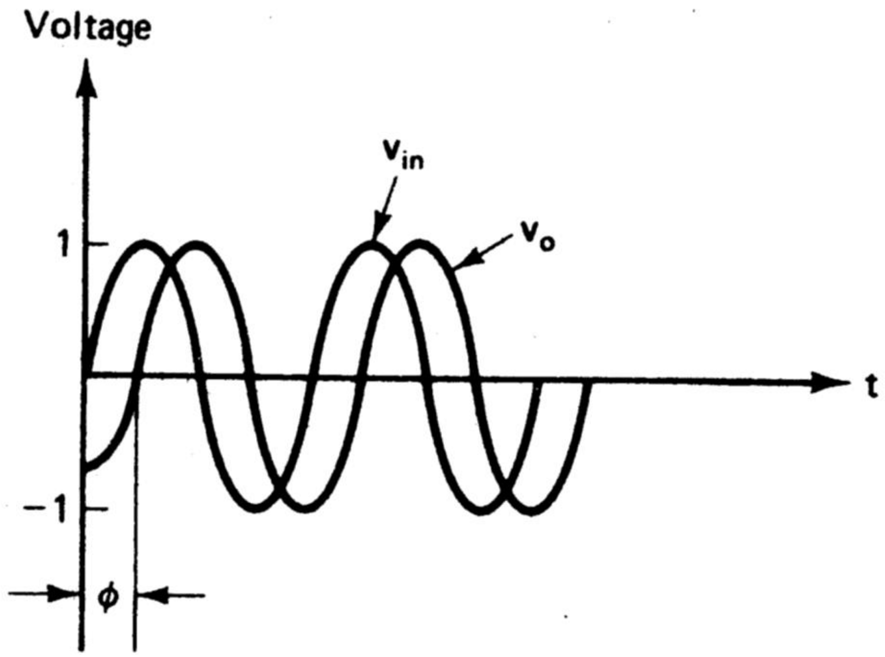
These filters will also have roll off characteristics





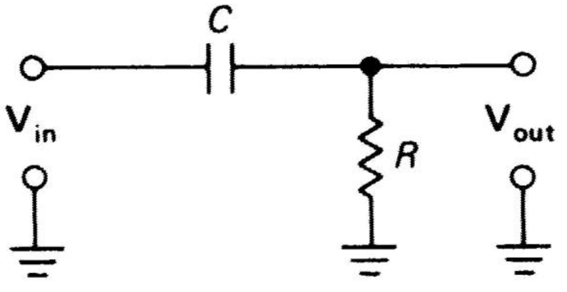
Filters

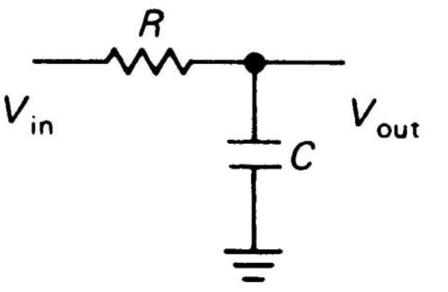
All pass filter - passes all frequencies well (no attenuation) with phase shift. Input voltage and output voltage is same for all the frequencies .



Passive filters

A simple RC circuit for high pass and low pass filter





High pass filter

A DC signal is fully blocked and high frequency signal is passed.

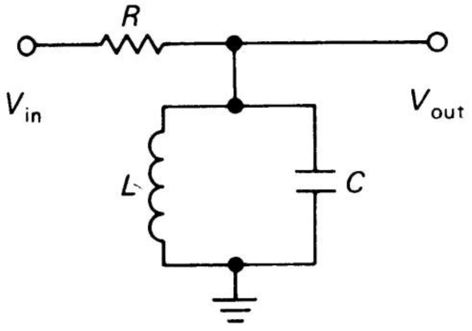
Low pass filter

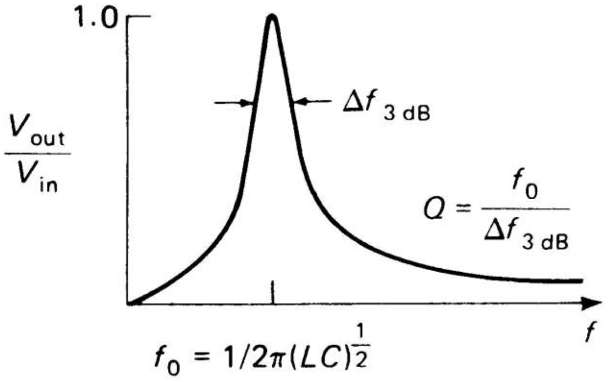
A DC signal is fully passed but high frequency signal goes to ground via capacitor.

Cut off frequency = $1/2\Pi RC$

Passive filters

A simple LC circuit for band pass



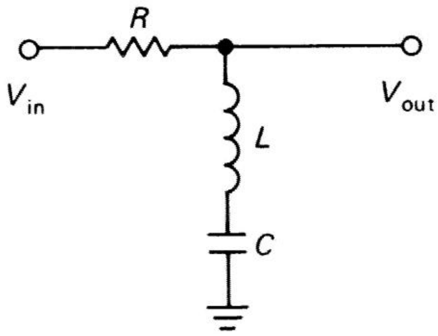


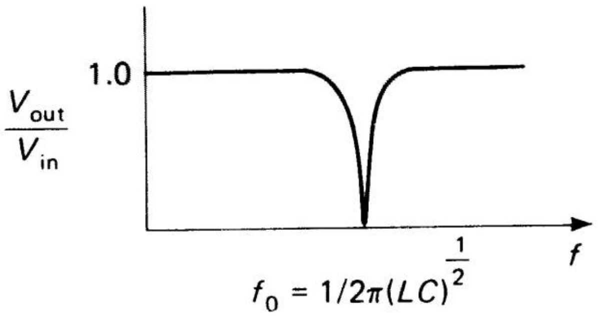
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

At resonant frequency the impedance is infinite and all the signal is passed

Passive filters

A simple LC circuit for band reject





$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

At resonant frequency the impedance is zero and all the signal is grounded

Active filters

When active components are used in the filter circuits then it is called as active filters. Transistors, opamp are active devices.

Active filters offer following advantage over passive filters

- Gain and frequency adjustment flexibility
- No loading problem
- Cost effective

Commonly used filters

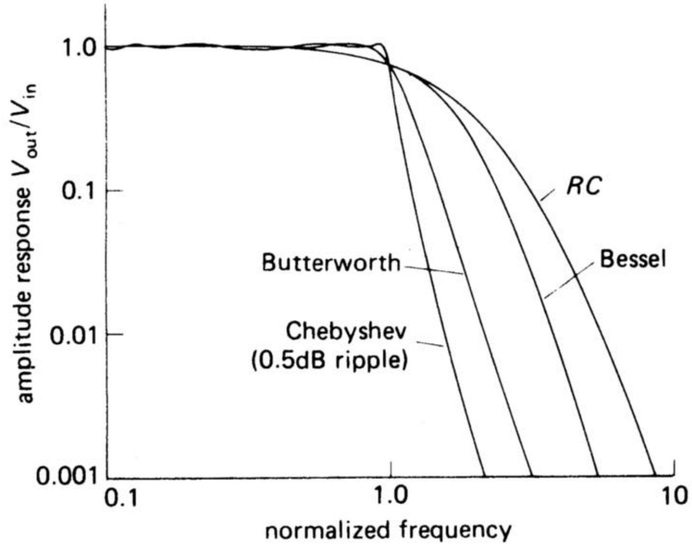
- Butterworth, Chebyshev, Cauer, Sallen Key etc. These filters have different characteristics in pass band and reject band.

Characteristics - Active filters

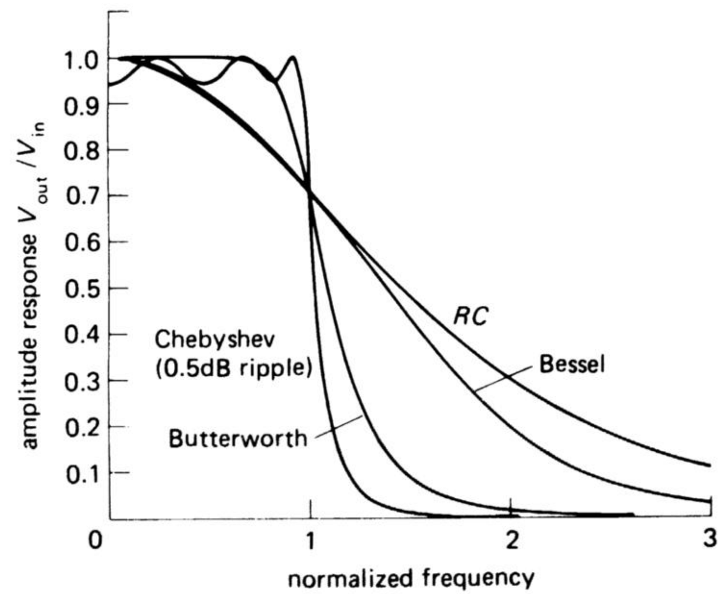
Butterworth – Maximally flat response in pass band

Bessel – Maximally flat time delay

Chebysev – Ripples in pass band, steepest transition from pass band to stopband.



A

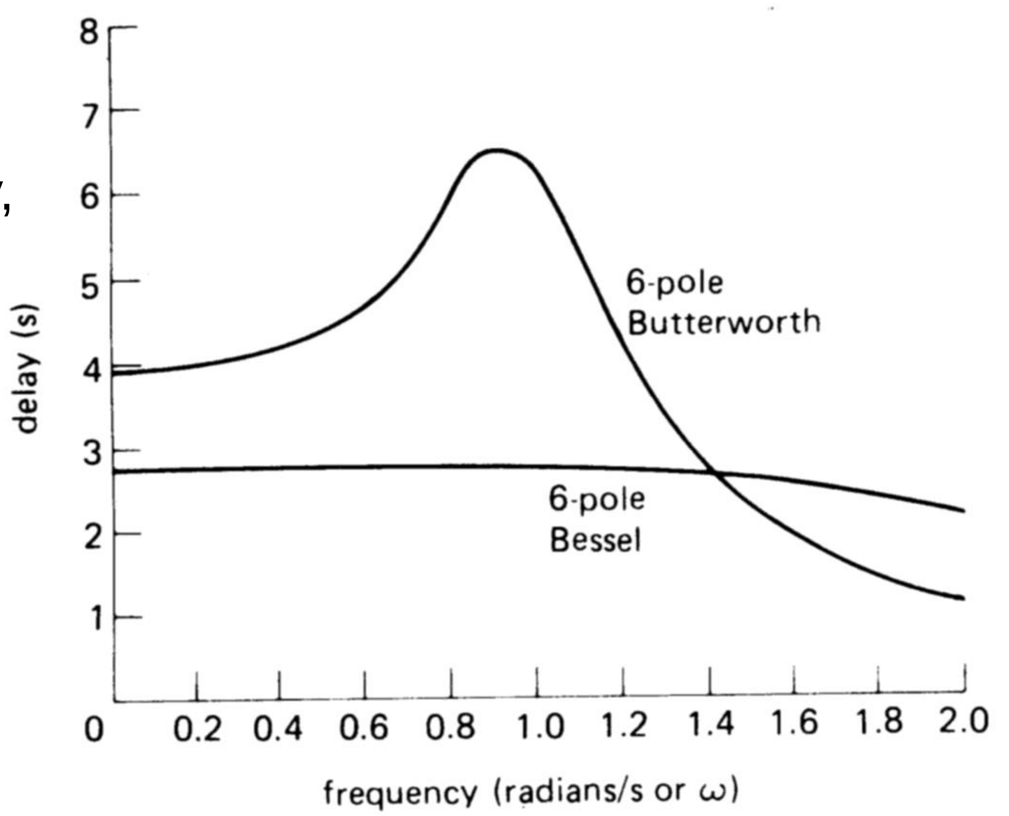


Characteristics - Active filters

Butterworth – Time delay is not constant, phase distortion is high

Bessel – Maximally flat time delay, constant phase delay

Very important when phase distortion is critical



First order Low pass Butterworth filter

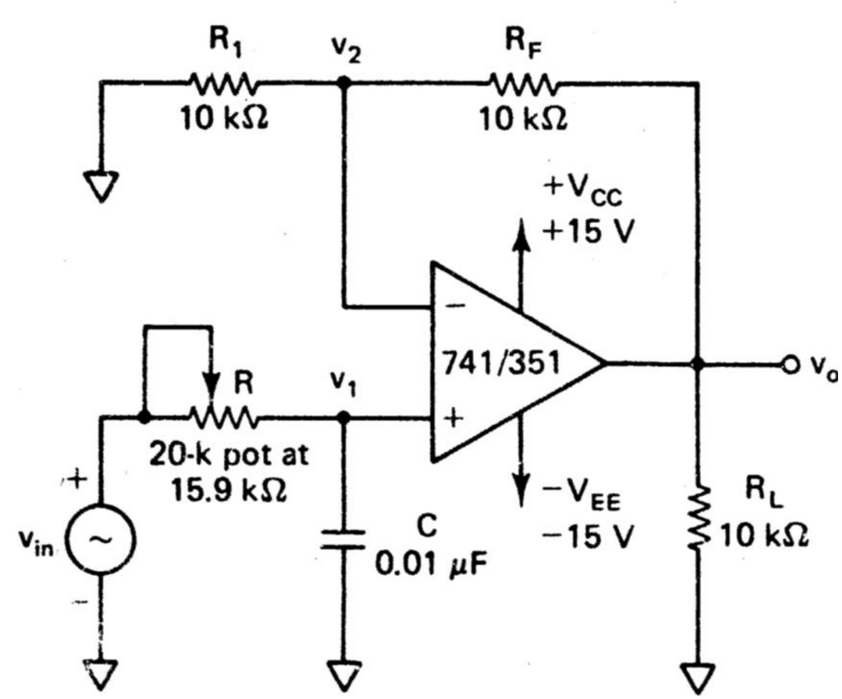
First order filter. Opamp is used in non-inverting mode, it will not load RC network. Resistor R_1 and R_F decide the gain of the filter.

$$\frac{v_o}{v_{in}} = \frac{A_F}{1 + j(f / f_H)} \qquad A_F = 1 + \frac{R_F}{R_1}$$

f is input frequency

f_H is higher cutoff frequency

$$f_H = \frac{1}{2\pi RC}$$



First orderLow pass Butterworth filter

Gain $$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F}{\sqrt{1+(f/f_H)^2}}$$

Phase angle $$\phi = -\tan^{-1}(f/f_H)$$

At very low frequency $f < f_H$

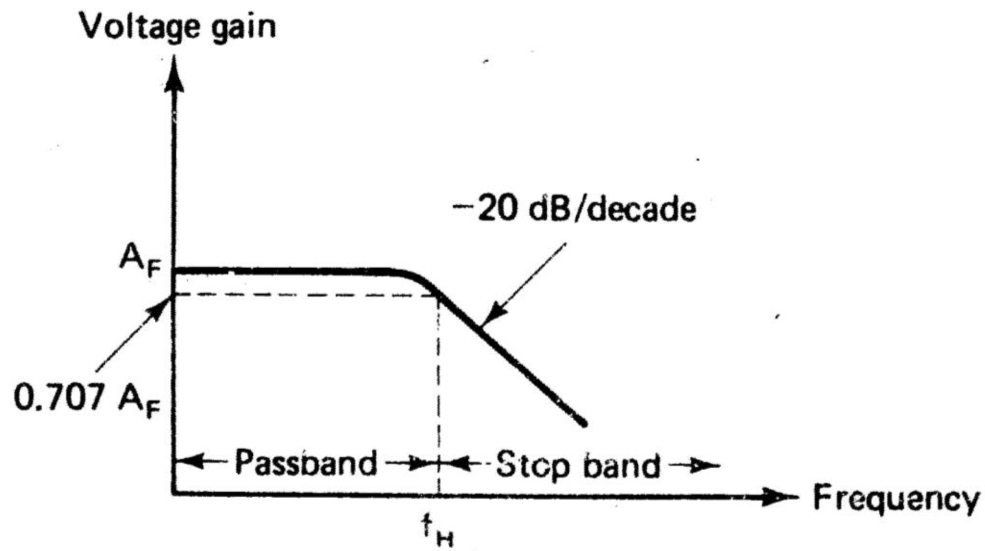
$$\left|\frac{v_o}{v_{in}}\right| \cong A_F$$

At frequency $f = f_H$

$$\left|\frac{v_o}{v_{in}}\right| = \frac{1}{\sqrt{2}} = 0.707$$

At frequency $f > f_H$

$$\left|\frac{v_o}{v_{in}}\right| < A_F$$



Second order Low pass Butterworth filter

Second order Butterworth filter, stop band respond is 40 dB per decade, double of first order filter. Adding additional RC network in the first order creates a second order filter.

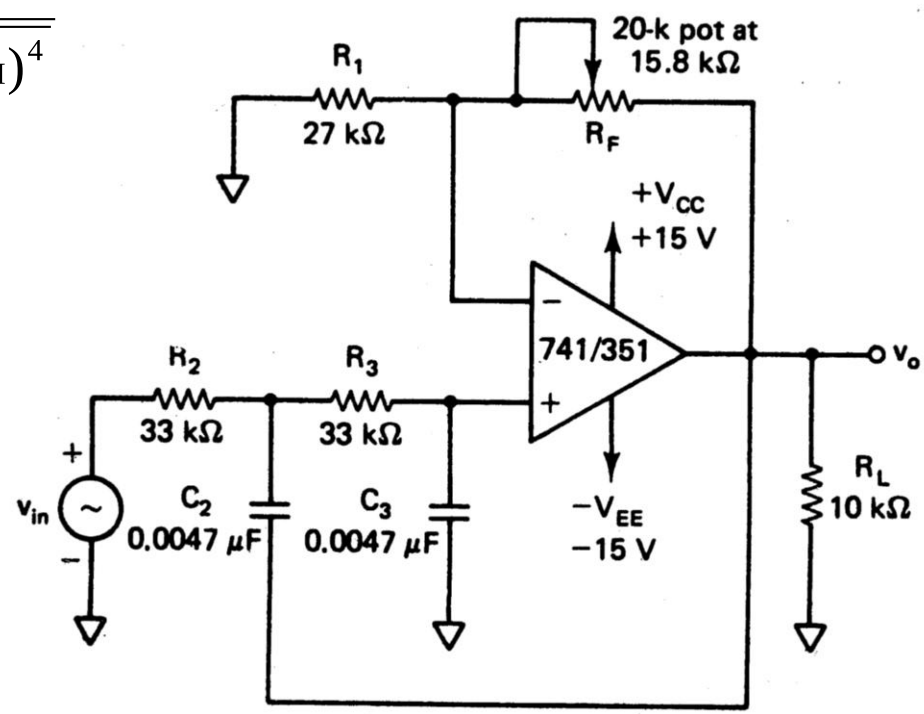
Gain is decided by R_F and R_1 Cutoff frequency f_H is decided by R_2 ,R_3 , C_2 and C_3

$$f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1+(f/f_H)^4}}$$

Pass band gain has to be 1.586 when $R_2 = R_3$, $C_2 = C_3$ for Butterworth performance

$$A_F = 1 + \frac{R_F}{R_1}$$



First order high pass Butterworth filter

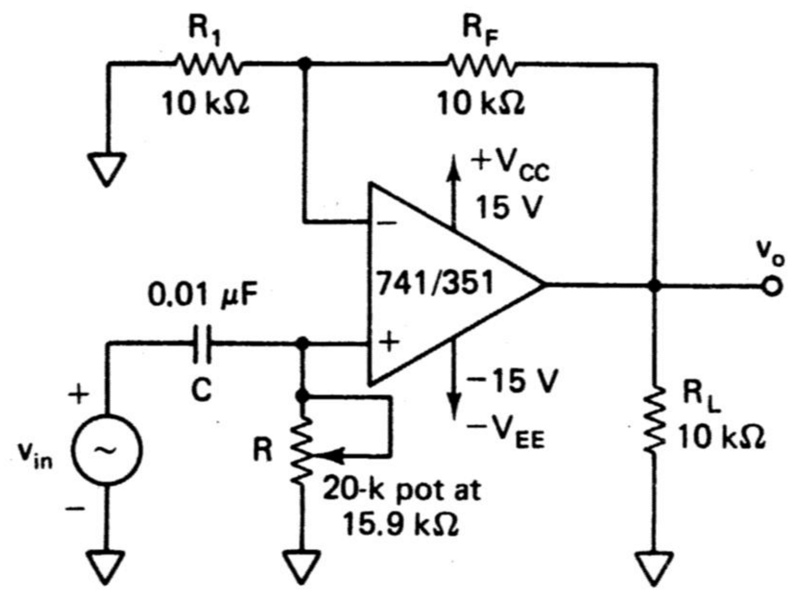
This filter can be obtained by interchanging the resistor and capacitor in low pass filter circuit

$$\left|\frac{v_o}{v_{in}}\right| = \frac{A_F(f / f_L)}{\sqrt{1+(f / f_L)^2}}$$

$$A_F = 1 + \frac{R_F}{R_1}$$

f_L is low cutoff frequency

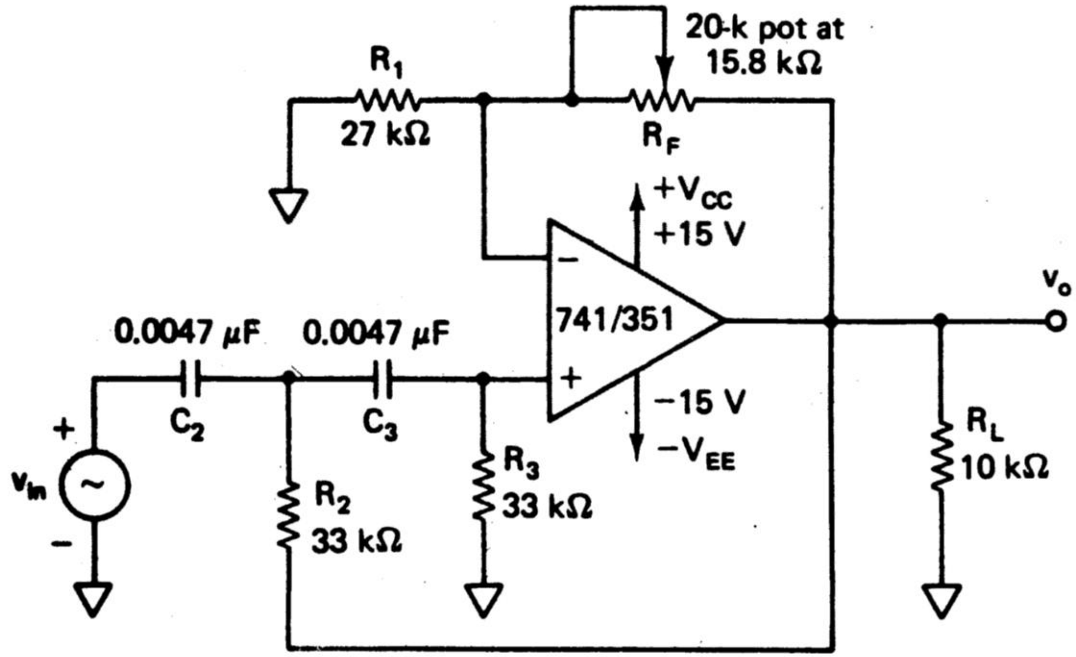
$$f_L = \frac{1}{2\pi RC}$$



Second order high pass Butterworth filter

Roll off is 40dB per decade, it can be created by changing resistors and capacitors in the second order low pass filter.

All calculations remain same as second order low pass Butterworth filter

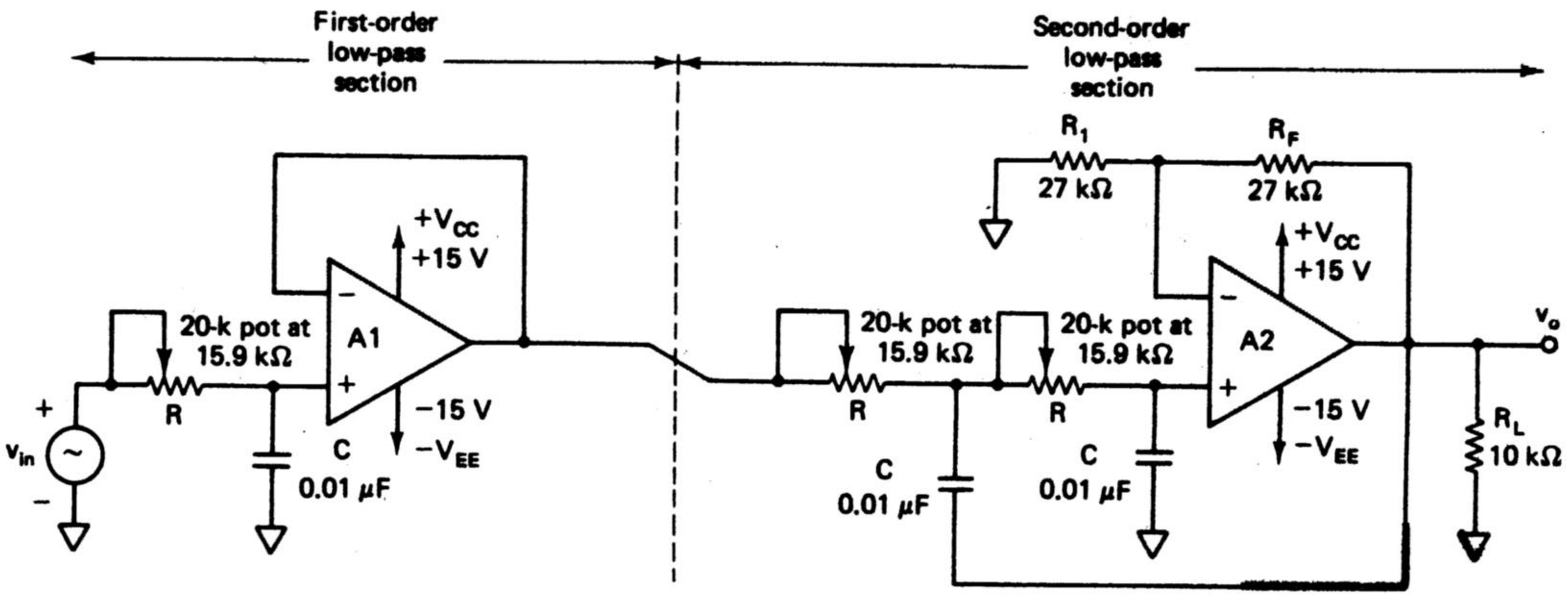


Higher order Butterworth filter

Higher order filters are created by cascading first order and second order filters. A third order low pass filter is combination of first order and second order low pass filters. Similarly a fourth order is combination of two second order. Overall gain will be the multiplication of individual gain of the stages involved.

Higher order Butterworth filter

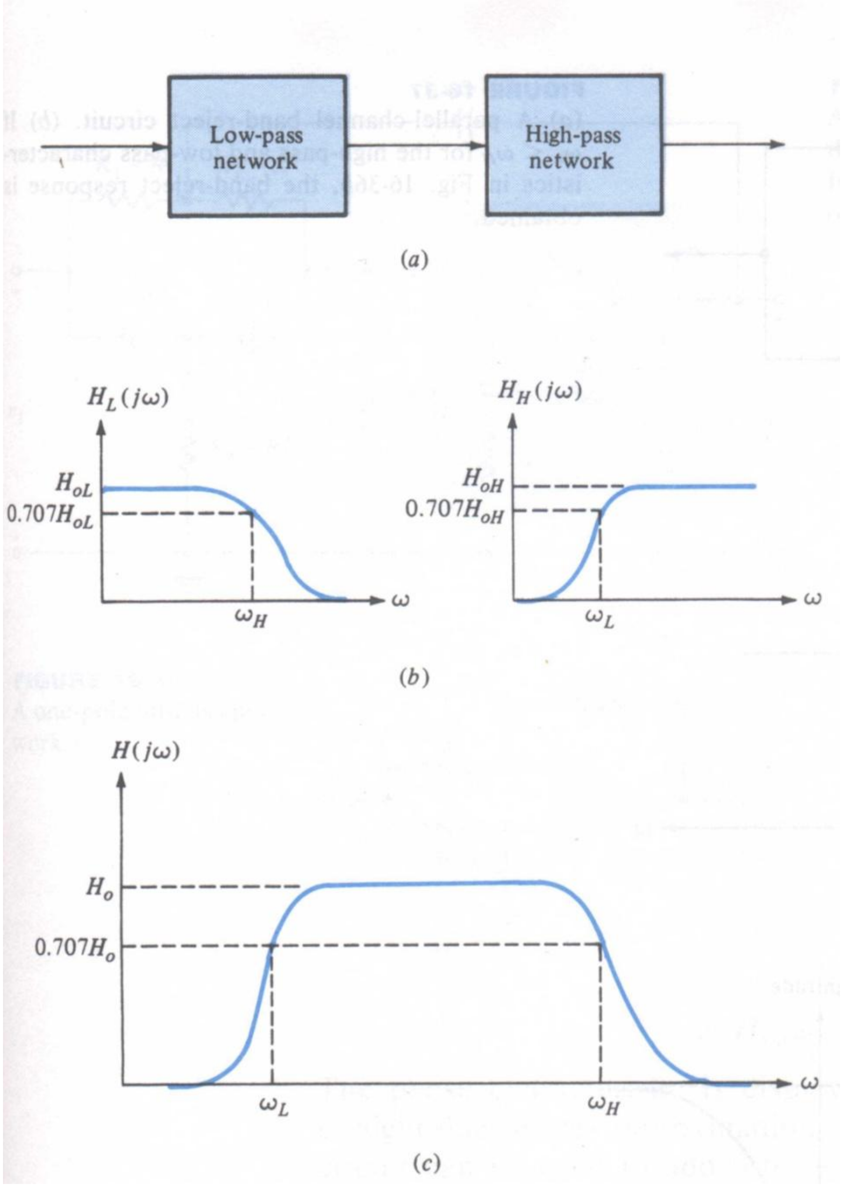
A third order low pass filter - first stage of low pass first order filter cascaded with second order low pass second order filter



(a)

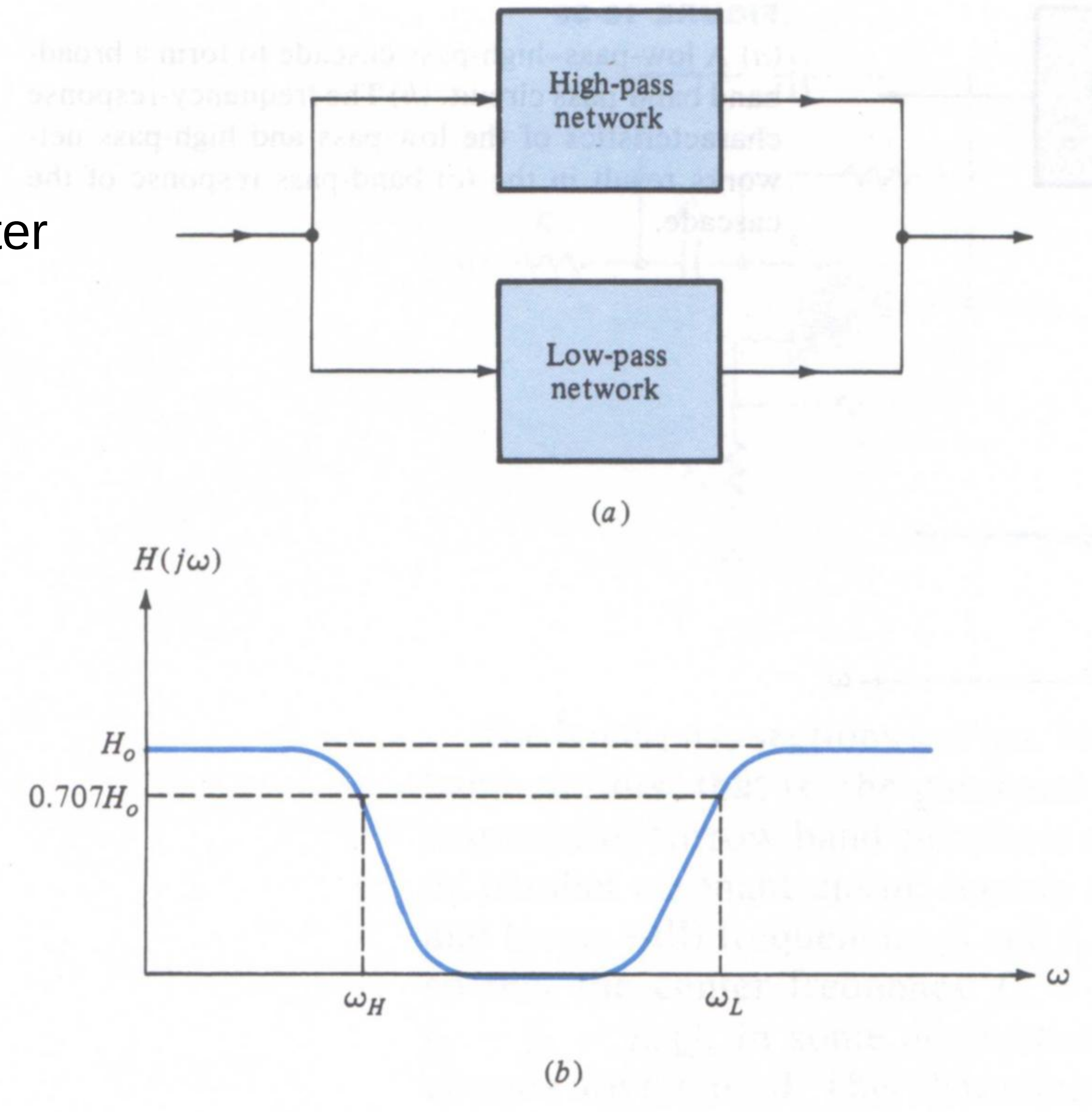
Band pass filter

Band pass filter is created using low pass & high pass filter in series. First low pass filter with high cutoff frequency in series with high pass filter cutoff frequency as low cut off frequency of band pass.



Band reject filter

Band reject filter is created using low pass & high pass filter in parallel. Low pass filter will attenuate all the frequencies above ω_H . And highpass will attenuate all frequencies below ω_L Band pass frequencies will be attenuated as a result



Band pass Butterworth filter

Band pass filters of two types : Wide band pass and narrow band pass

Let f_h = high cutoff frequency and f_L low cutoff frequency

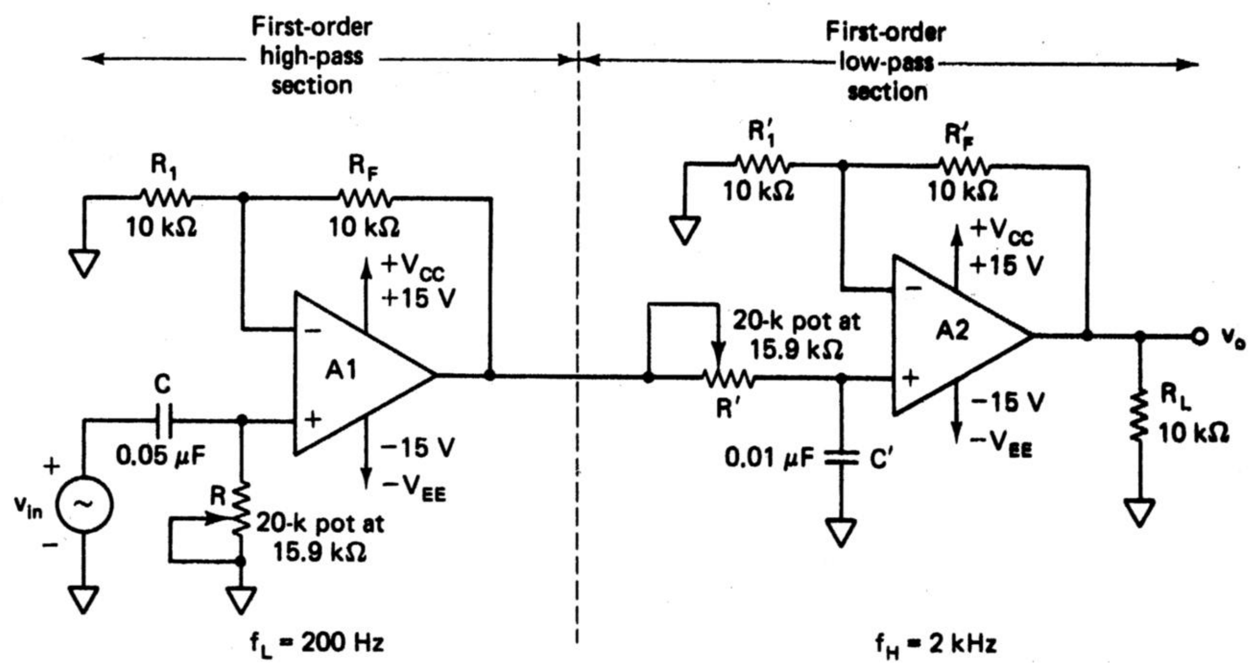
Wide band pass filters have Quality factor Q < 10 and narrow band pass filters have Q > 10

$$Q = \frac{f_c}{BW} = \frac{f_c}{f_H - f_L} \qquad f_c = \sqrt{f_H f_L}$$

f_H = high cutoff frequency, f_L = low cutoff frequency

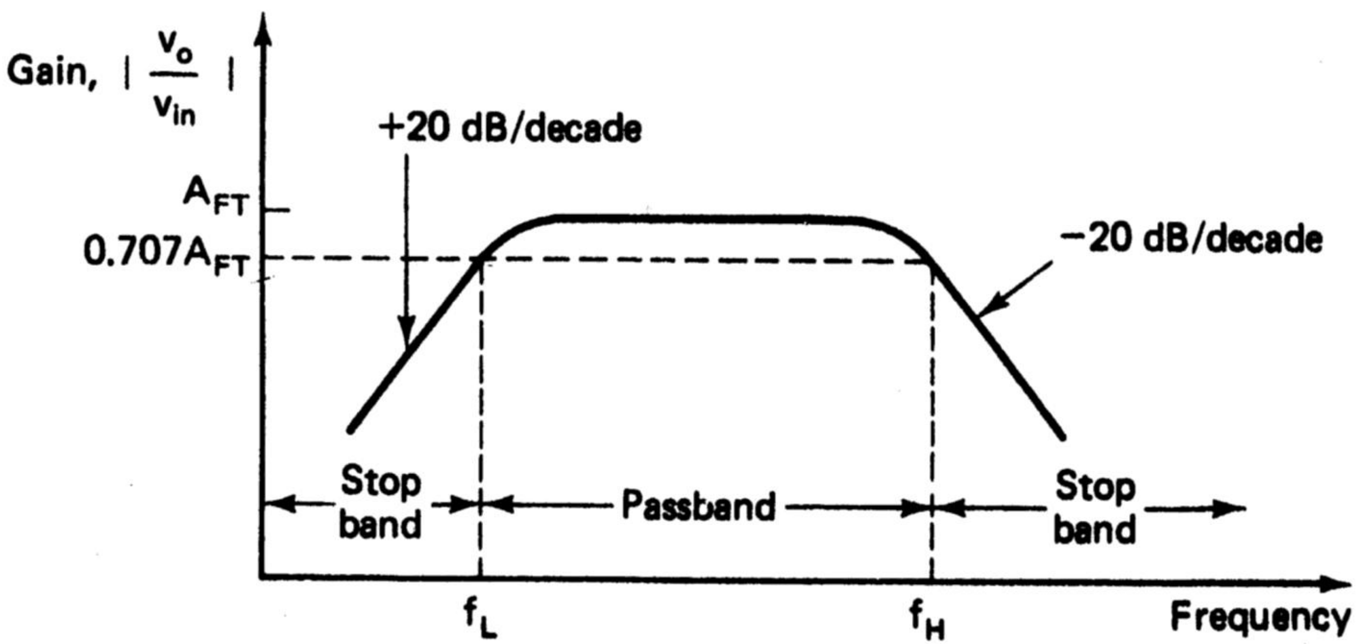
Wide band pass Butterworth filter

Wide band pass filters are created by cascading high pass and low pass filters. First it will pass all the high frequency above low cutoff frequency, f_L and next stage will stop below high cutoff frequency, f_H



Wide band pass Butterworth filter

All relations for individual filters are applicable and overall gain will be multiplication of individual stages. Roll off characteristics are dependent on the individual stages.



Narrow band pass filter

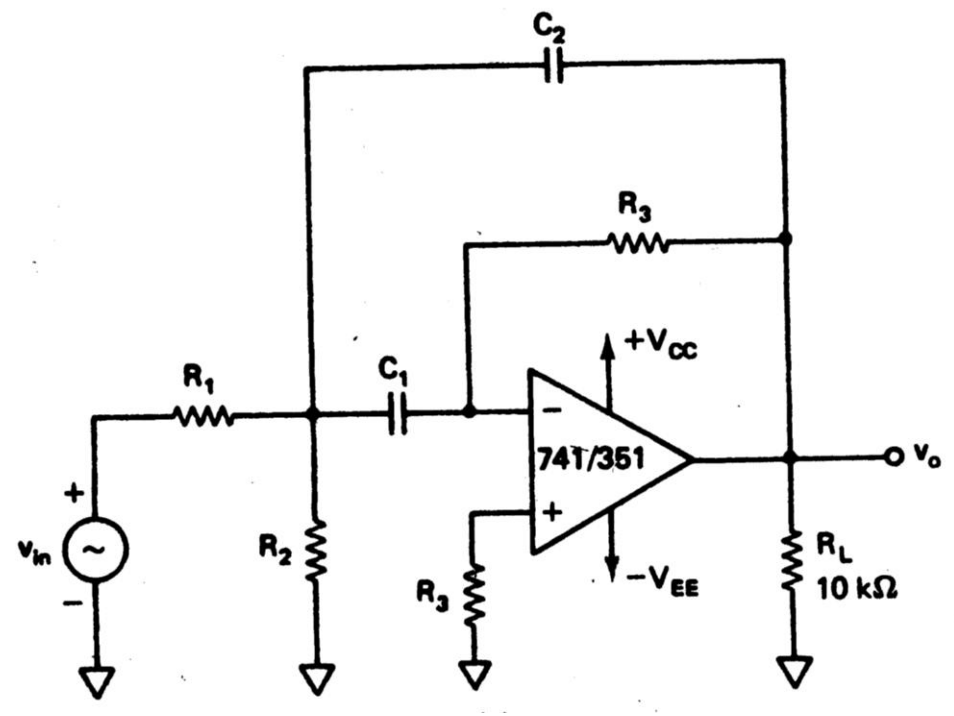
Narrow band pass filter uses multiple feed back path. And also opamp is used in inverting mode

Generally designed for specific value of Q and f_C

$$C = C_1 = C_2 \qquad R_1 = \frac{Q}{2\pi f_C C A_F}$$

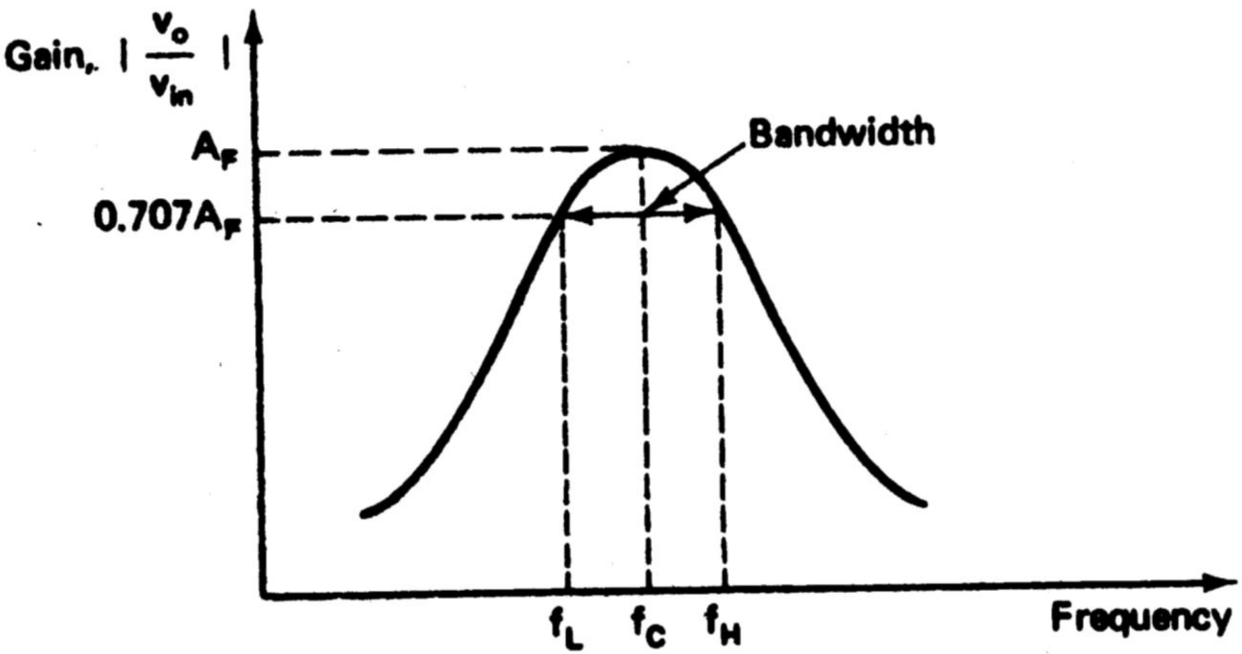
$$R_2 = \frac{Q}{2\pi f_C C(2Q^2 - A_F)}$$

$$R_3 = \frac{Q}{2\pi f_C C} \qquad A_F = \frac{R_3}{2R_1}$$



Narrow band pass filter

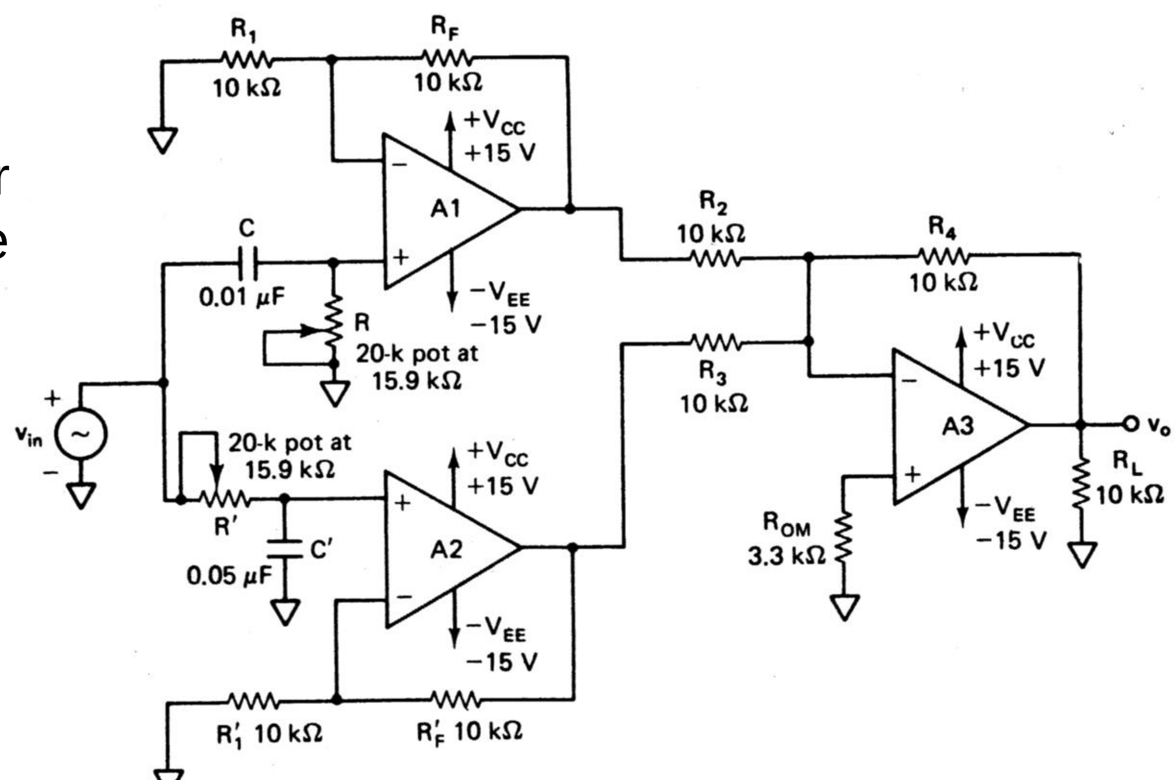
Maximum Gain A_F at center frequency f_C



Wide band reject Butterworth filter

These are also called as band-stop or band-elimination filters. Wide band reject and narrow band reject filters depending on Q.

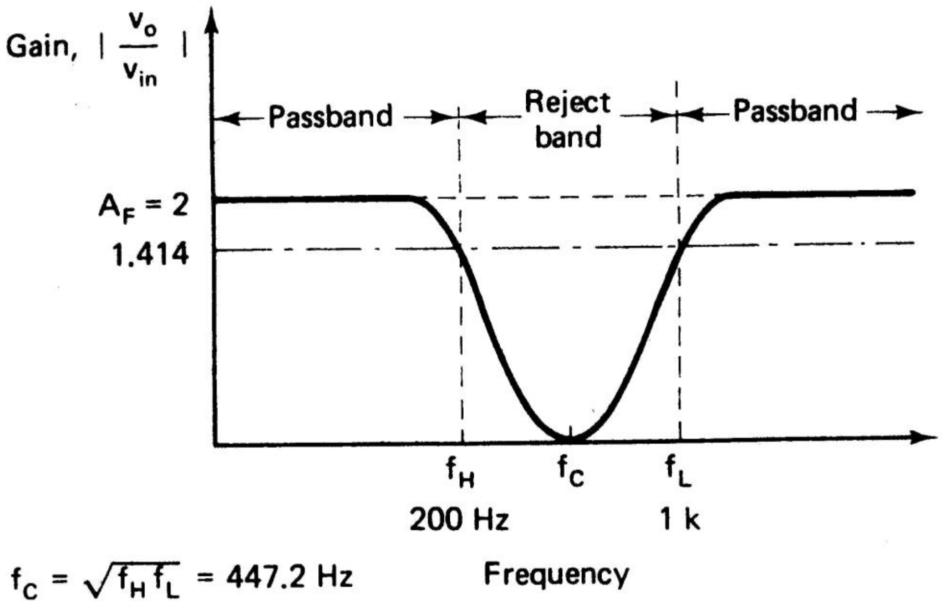
Input signal is passed through high pass and low pass filter parallel and later summed to obtain the wide band reject filter



(a)

Wide band reject Butterworth filter

Maximum attenuation is at center frequency f_C Roll off characteristics are same as first order Butterworth filter



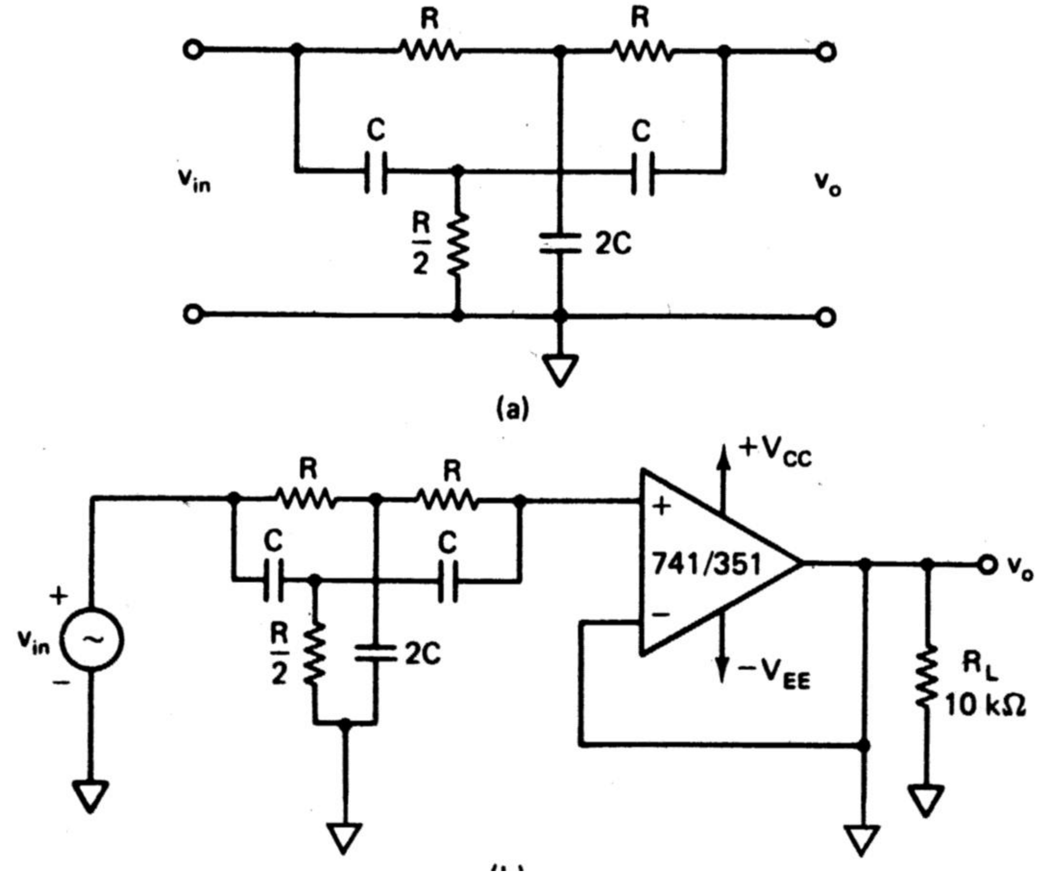
Narrow band reject filter

Narrow band reject filter also called as notch filter, used to remove single frequency like 60Hz hum. Designed using twin-T network of RC.

$$f_N = \frac{1}{2\pi RC}$$

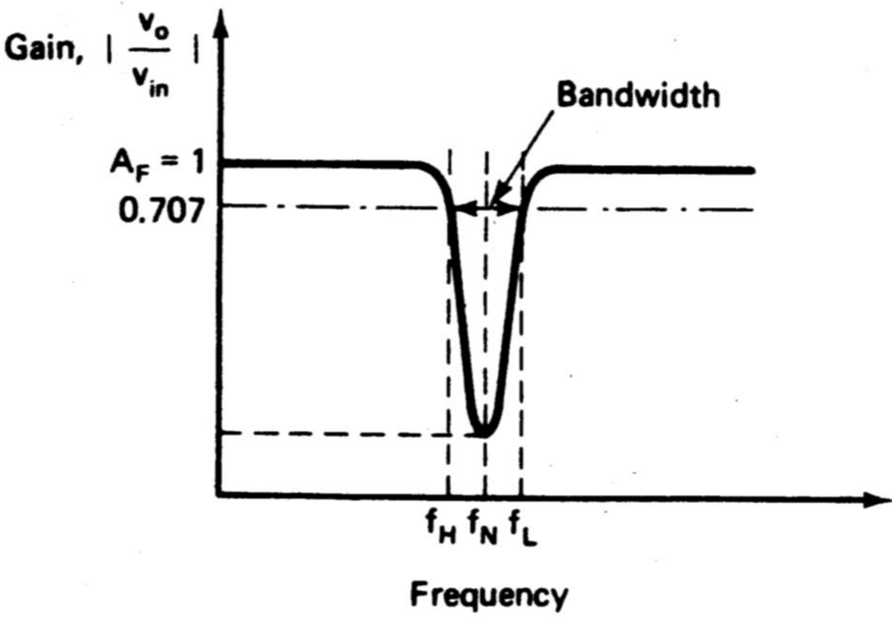
f_N is notch frequency

Voltage follower improves the figure of merit Q of passive RC network



Narrow band reject filter

Maximum attenuation occurs at f_N Other frequencies are passed faithfully



All pass filter

Passes all the frequency components of the input signal without attenuation with predictable phase shift. Signal transmitted over telephone lines undergo change in phase and such circuits are used for compensating phase change.