Klystron

3.1 Conventional Tubes

- The triodes, pentrodes and tetrodes are known as conventional tubes. These tubes are only useful at low microwave frequencies. The vacuum tube was the first active electronic device, capable of actually controlling and amplifying a small signal. It was invented in 1907 by De Lee Forest. The basic elements of the vaccum tube are shown in Fig. 3.1.1.

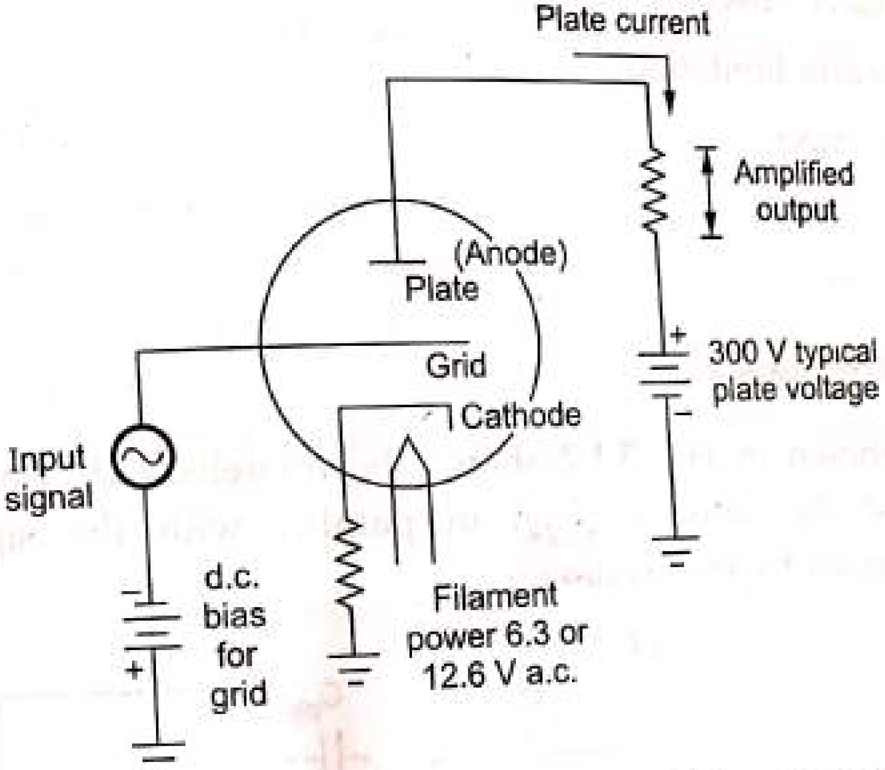

Fig. 3.1.1 Functional schematic diagram of Vacumme tube triode

- The filament heats up from applied a.c. or d.c. and it causes the surrounding cathode to emit electron. Anode plate is charged to a high positive d.c. voltage and attracts the electrons emitted by cathode. Due to the flow of electrons between cathode and anode, the plate current generated and amplified output is produced across the load. The load may be an antenna, filter, a modulation and demodulation circuit. The intermediate component between cathode and anode plate is grid which is used to control the flow of electrons by varying the voltage. When grid voltage is varying from zero to negative, then the larger flow of electrons between cathode and anode is controlled and modulated. Small vaccum tubes were available for microwave and millivolt signals but have been replaced by transistors.

3.1.1 Limitations of Conventional Tubes at Microwave Frequencies

- The size of electronic devices required for generation of microwave energy becomes very smaller at microwave frequencies. Because of small size, these devices increased the noise levels and results in lesser power handling capacity. So, at the microwave frequencies, the microwave tubes are used because they can provide higher output power, lesser noise, better reliability with reduced output power levels. Due to some characteristics the conventional tubes and transistors are not used at high frequencies mentioned below :

i) Interelectrode capacitances

ii) Lead inductance effect

iii) Gain bandwidth limitation

iv) Transit time effect

v) Skin effect

vi) Dielectric losses

i) Interelectrode capacitance

- The circuit shown in Fig. 3.1.2 shows the interelectrode capacitance between the grid and the cathode (C_{gk}) in parallel with the signal source. The reactance is given by the relation :

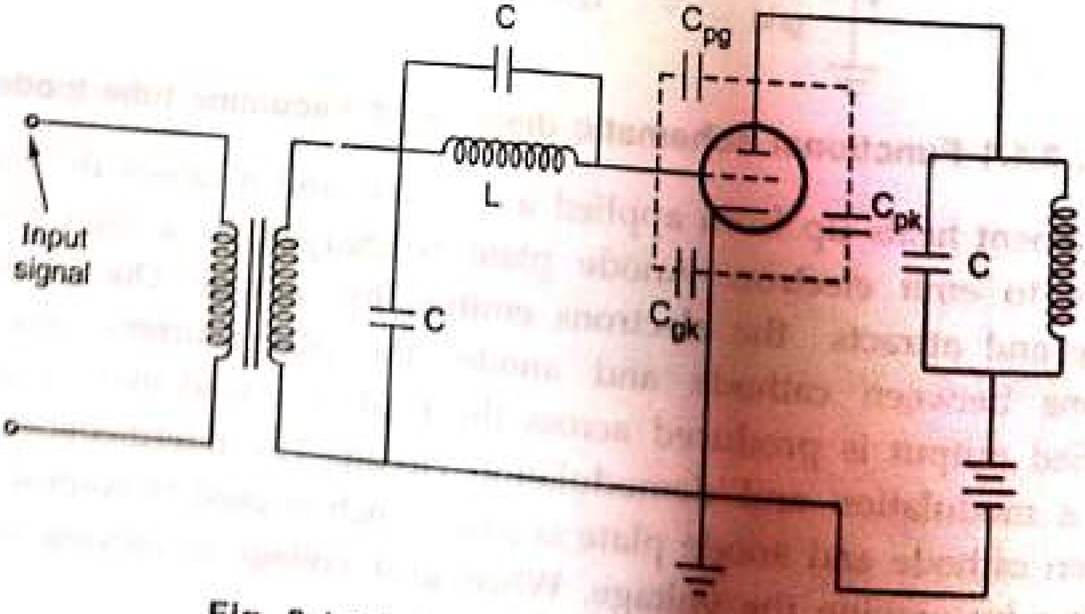

Fig. 3.1.2 Interelectrode capacitance

$$X_C = \frac{1}{2\pi fC}$$

- As the interelectrode capacitance decreases the reactance of interelectrodes increases. As the frequency of the input signal increases, the effective grid to cathode impedance of the tube decreases because of a decrease in the reactance of the interelectrode capacitance. When the signal frequency is greater than 100 MHz, then the reactance of the grid to cathode capacitance is so small that much of the signal is short circuited with the tube. Since the electrode capacitances are effectively in parallel with the tuned circuits, as shown in above circuit, they will also affect the frequency at which the tuned circuit resonate. This effect is minimized by using the smaller electrodes and by increasing the distance between electrodes.

ii) Lead inductance effect

- The lead inductances within a tube are effectively in parallel with the interelectrode capacitances. The reactances is given by relation :

$$X_L = 2\pi fL$$

- As the lead inductance increases, the reactance of the circuit also increases. This effect raise the frequency limit of the tube. The inductance of cathode lead is common to both the grid and plate circuits. This provides a path for degenerative feedback which reduces the overall circuit efficiency. This effect is minimized by using the larger sized short leads without base pins.

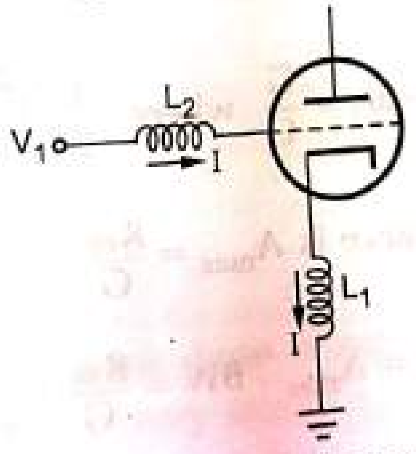

Fig. 3.1.3 Lead inductance

iii) Gain bandwidth limitation

- To achieve the maximum gain, the vaccum tubes generally use the circ shown in Fig. 3.1.4. Replacing R_P and R_L by R.

$$R = \frac{1}{R_P} + \frac{1}{R_L}$$

$$G = \frac{V_0(s)}{V_i(s)} = Z_0(s)$$

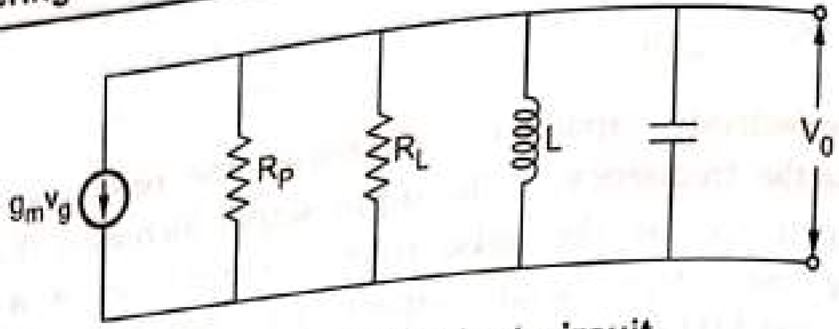

Fig. 3.1.4 Equivalent circuit

$$\frac{1}{Z_0(s)} = Y_0(s) = Cs + \frac{1}{Ls} + \frac{1}{R} = \frac{s^2LCR + Ls + R}{RLs}$$

$$Z_0(s) = \frac{s/C}{s^2 + \frac{3s}{CR} + \frac{1}{LC}}$$

- From the characteristic equation of the denominator, the roots give the values of lowest and highest frequencies ω_1 and ω_n.

$$\omega_1 = -\frac{G}{2C} - \sqrt{\left(\frac{G}{2C}\right)^2 - \frac{1}{LC}}$$

$$\omega_n = -\frac{G}{2C} + \sqrt{\left(\frac{G}{2C}\right)^2 - \frac{1}{LC}}$$

$G = \frac{1}{R}$ (conductance is always reciprocal of resistance)

$$\text{Bandwidth} = \omega_n - \omega_1 = \frac{G}{C} \quad \text{where} \left(\frac{G}{2C}\right)^2 >> \frac{1}{LC}$$

The maximum gain at resonance is $A_{max} = \frac{g_m}{G}$

$\therefore$ Gain bandwidth product $= A_{max} \cdot BW = \frac{g_m}{G} \times \frac{G}{C} = \frac{g_m}{C}$

- As shown in above relation, the gain bandwidth product is independent of frequency. Higher gain for a given tube can be achieved only by using the narrow bandwidth. This restriction is applicable to its resonant circuit only. To obtain an overall high gain over a broad bandwidth in microwave devices slow wave structures are used.

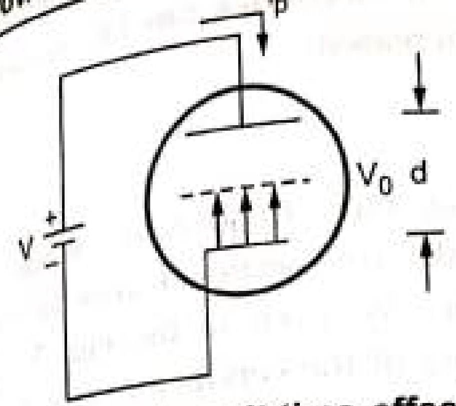

Fig. 3.1.5 Transit-time effect

iv) Transit time effect

- Transit time is the time required for electrons to travel from the cathode to the anode plate. If we consider the circuit of a simple vaccum tube as shown in Fig. 3.1.5. When 'd' is the distance between two plates, i_p is plate current, V is applied input voltage, V_0 is output voltage.

Calculation for Transit Time : By definition, Transit Time is given by :

$$\tau = \frac{d}{v_0} \quad \text{where } v_0 \text{ is velocity of electrons}$$

Static energy of electrons = eV

Kinetic energy of electrons = eV

Kinetic energy of electrons = $\frac{1}{2} m v_0^2$

We know that under equilibrium state the static energy of electrons is equal to kinetic energy of electrons.

$$eV = \frac{1}{2} m v_0^2$$

$$v_0 = \sqrt{\frac{2eV}{m}}$$

$$\tau = \frac{d}{\sqrt{\frac{2eV}{m}}}$$

- At low frequencies, the transit time effect is negligible because distance between anode and cathode is very small.
- But at higher frequencies, the transit time is large as compared to the period of microwave signal. The potential between the cathode and grid may alternate from 10 to 100 times during the electron transmit.
- The grid potential during the negative half cycle thus removes energy that was given to the electron during the positive half cycle. Consequently, the electrons may oscillates back and forth in the cathode grid space or return to the cathode. The overall result of transit time effects is to reduce the overall efficiency of the vaccum tube.

- To minimize this effect, the separation between electrodes can be decreased and the plate to cathode potential 'V' can be increased.

v) Skin effect :

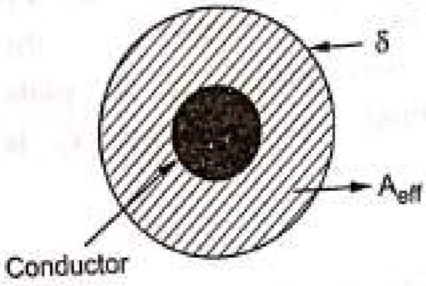

Fig. 3.1.6

- This effect introduces at high frequencies, when the current flows from small cross-sectional area to outer surface of the conductor. As given in the Fig. 3.1.6 is skin depth (wall thickness of the conductor) and A_{eff} is the effective area over which the current flows.

$$\delta = \text{skin depth} = \sqrt{2/\omega\mu\sigma}$$

$$\delta \propto \frac{1}{\sqrt{\omega}}$$

$$\delta \propto A_{eff}$$

$$A_{eff} \propto \frac{1}{\sqrt{f}}$$

Resistance is given by relation

$$R = \frac{\rho l}{A_{eff}}$$

$$R = \rho l \cdot \sqrt{f}$$

- As the frequency increases the resistance of the conductor increases, due to this higher frequency losses are produced.

vi) Dielectric losses

- These are different insulating materials which are used as a glass envelope, silicon plastic encapsulations in different microwave devices. The loss in any of these material is in general related to power loss given by :

$$P = \pi f . V_0^2 \varepsilon_r \tan\sigma$$

where ε_r = Relative permittivity of dielectric

δ = Loss angle of dielectric

P = Power loss

- At higher frequencies, the power loss increases. To eliminate these losses the surface area of glass should be decreased and the tube base should be eliminate.