7

Klystrons

The principal limitations of conventional negative grid electron tubes are :

1. Electron transit time which becomes a noticeable proportion at high frequencies.

2. Lumped electrical reactances and law Q resonant circuits. There are some severe limitations on conventional tubes which make their operation relatively poor at UHF and VHF.

The multicavity klystron and for that matter the various devices described in this chapter and the following chapter are based on the principal that "if you cannot break them, join them"; *i.e.* to say that the transit time effect which forbids the use of conventional tubes at UHF/VHF is put to effective use in the operation of devices like Klystron, Magnetron etc.

7.1. Klystron

A klystron is a velocity modulated tube, in which the velocity modulation process produces a density modulated stream of electrons. The earliest form of velocity variation device is the "Two cavity klystron amplifier", whose schematic diagram is shown in Fig. 7.1. It is seen that a high velocity electron beam is formed, focussed and sent down along glass tube to a collector electrode, which is a high positive potential with respect to the cathode. Magnetic focussing is used here, but the arrangement has not been shown in the figure for the sake of simplicity. As it is clear from the schematic Fig. 7.1 a two cavity klystron amplifier consists of a cathode, focussing electrodes, two buncher grids separated by a very small distance forming a gap A, two catcher grids with a small gap B followed by a collector. The significance of buncher and catcher grids will be clear from the following discussion.

The input and output are taken from the tube *via* resonant cavities (refer to chapter on microwave components for details). The separation between buncher grids and catcher grids is called *drift space*. The electron beam passes gap A in the buncher cavity to which RF signal to be amplified is applied and is then allowed to drift freely without any influence from Rf. fields until it reaches gap B in the output or catcher cavity.

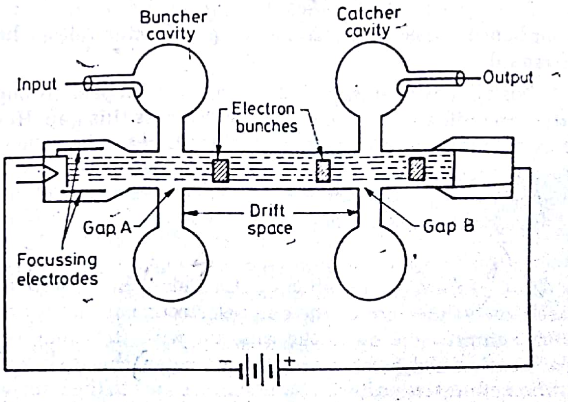

Fig. 7.1. Schematic diagram of a klystron amplifier.

The first grid (focussing grid) controls the number of electrons in the electron beam and serves to focus the beam. The velocity of electron in the beam is determined by the beam accelerating potential. On leaving the region of first grid, the electrons pass through the grids of buncher cavity. The grids of the cavity allow the electrons to pass through, but confine the magnetic fields within the cavity. The space between the grids is referred to as *interaction space*. When electrons travel through this space they are subjected to RF potentials at a frequency determined by the cavity resonant frequency or the input frequency. The amplitude of this *RF* potential between the grids is determined by the amplitude of the incoming signal in case of the amplifier, or by the amplitude feedback signal from the second cavity if used as an oscillator. If all goes well, oscillations will be excited in the second cavity which are of a power much higher than in the buncher cavity, so that a large output can be taken.

As it is seen that the cavities are re-entrant type and are also tunable. Further more, they may be integral or demountable; in the latter case the wire grid meshes may be connected to the rings external to the glass envelope, and cavities may be attached to the rings. Although the drift space is quite long and the transit time in it is put to use, the gaps must to be short that the voltage across them does not change significantly during the passage of a particular bunch of electrons ; having a high collector voltage helps in this regard.

It has already been said that when electrons pass through gap *A*, they are influenced by the RF voltage across this gap. However, the extent of this effect on any electron will depend on the voltage across the gap, at the time the electron passes this gap. It thus becomes necessary, to investigate the effect of the gap voltage upon passing electrons individually.

7.1.1. Velocity Modulation. Consider the situation when there is no voltage across the gap ; electrons passing it are unaffected and continue on to the collector with the same constant velocities they had, before approaching the gap (this is shown in Fig. 7.2). Sometime later, after an input has been fed to the buncher grid, an electron will pass gap *A* at the time when the voltage across this gap is zero and going positive, let this be the reference electron *y*. This reference electron is unaffected by the gap, as evidenced by the fact that it has the same slope on the "Applegate diagram" of Fig. 7.2, as electrons passing the gap before any signal was applied to the buncher cavity.

Another electron *z*, passes the gap slightly later than *y*, as shown. In absence of gap voltage, both electrons would have continued past the gap with unchanged velocity and, therefore, neither would have caught up with the other. In presence of positive voltage across gap *A*, however electron *z* is accelerated slightly and given enough time, will catch up with the reference electron *y* easily before gap *B* is approached. Similarly, electron *x* passes gap *A* slightly before the reference electron, and is retarded by the negative voltage, at that instant across the gap ; since electron *y* was not so retarded, it has an excellent chance of catching electron *x*, before gap *B*, and this is done as shown in Fig. 7.2.

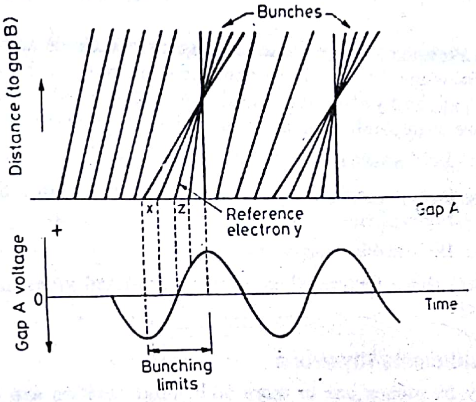

Fig. 7.2. Applegate diagram for klystron amplifier.

As electrons pass the buncher gap, they are *velocity modulated* by the RF voltage existing across this gap ; such velocity modulation is not sufficient in itself for amplification, by the klystron. However, as explained with reference to the Applegate diagram, the electrons are given an opportunity to bunch in the drift space. When an electron catches up with another one, it may simply pass it and forge ahead ; on the other hand, it may exchange energy with the slower electron, giving it some excess energy, and the two bunch together and move on with the average velocity of the beam. As the beam progresses further down along the drift space, the bunching becomes more complete, as more and more of the faster electrons catch up with bunches ahead. Eventually, the current passes the catcher gap with quite pronounced bunches and, therefore, varies cyclically with time, and this variation in current density (often called current modulation) enables the klystron to have a significant gain.

It is noted that (reference to Applegate diagram) bunching can occur only once per cycle, centering on the reference electron. The limits of bunching are also shown, any electrons arriving slightly after the second limit are not accelerated sufficiently to catch the reference electron and that the reference electron cannot catch up with any electron passing through the gap *A* just before the first limit. Bunches, therefore, arrive at the catcher grid, once per cycle and then deliver energy to this cavity. The catcher cavity is excited into oscillations at its resonant frequency (which is same as the input frequency) and a large sinusoidal output can be obtained because of the flywheel effect of the output resonator. Bunching, therefore, is dependent upon the following parameters.

1. Drift space should be properly adjusted.
2. Signal amplitude should be such that proper bunching takes place.
3. D.C. anode voltage.

Above three factors when properly adjusted gives maximum efficiency.

7.2 Multi-cavity Klystrons

Very frequency one or more additional cavities are inserted between the catcher and buncher cavities, here oscillations are excited in the middle cavity by the partially bunched electron stream passing the gap B ; in this way a voltage is produced across B that also acts on the electron stream. By detuning the additional cavity so that its gap offers an impedance having an inductive component (*i.e.* resonant frequency slightly above the signal frequency), the phase of the voltage across B is related to the electron stream at B in such a manner as to cause further velocity modulation. (The schematic diagram of a 3 cavity klystron is shown in Fig. 7.3). This very considerably increases the voltage amplification of the tube and likewise raises the efficiency. It is also possible to increase the BW of a klystron amplifier by employing one or more intermediate cavities that are properly tuned.

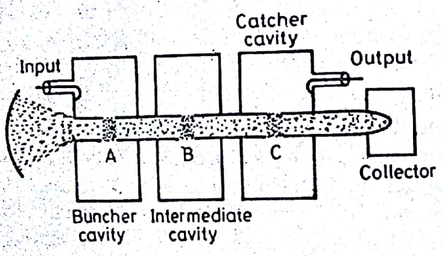

Fig. 7.3. Three cavity klystron.

7.3. Mathematical Analysis of Two Cavity Klystron

The following assumptions are made before the analysis is made:

(1) Electron transit angle in buncher and catcher grids is very small.

(2) $V_1 \leq V_o$, where V_1 is the amplitude of RF signal voltage at buncher grid, V_o is accelerating voltage.

(3) Space charge effects are neglected.

(4) Electron beam density is uniform throughout the length, *i.e.* no loss of electrons takes place in buncher and catcher grids. Analysis is now made with reference to Fig. 7.4.

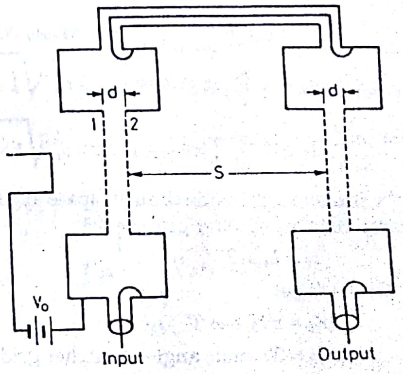

Fig. 7.4. Two cavity klystron.

In Fig. 7.4,
d = Interaction gap
s = Drift space
V_o = Accelerating voltage.

We know from the very well known relation that

$$v_o = \sqrt{\frac{2eV_o}{m}} \qquad \ldots(7.1)$$

$$\left[\because \; eV_o = \frac{1}{2} m v_o^2\right]$$

Voltage at grid 1 = V_o

Voltage at grid 2 = $V_o + V_1 \sin \omega t_1$.

In the above relation, v_o represents electron velocity at grid 1 of buncher grid and $V_1 \sin \omega t_1$ is the feedback voltage to the buncher cavity from catcher cavity.

Also
$$\frac{1}{2}mv_1^2 = e(V_o + V_1 \sin \omega t_1) \qquad \text{...(7.2)}$$

(Electrons come out of buncher grid 2 at time t_1 and velocity v_1)

From relation (7.2) and (7.1), we get
$$v_1 \equiv v_o\sqrt{1+\frac{V_1}{V_o}\sin \omega t_1} \qquad \text{...(7.3)}$$

Eq. (7.3) is obtained provided $V_1 << V_o$. This is an equation of velocity modulation for centre of bunch electron, *i.e.* when $\omega t_1 = 0$,

we get
$$v_1 = v_o.$$

$$\left.\begin{aligned}&\text{When} && \omega t_1 = +\frac{\pi}{2}, \text{ it gives } v_{1\max} = v_o\sqrt{1+\frac{V_1}{V_o}}\\ &\text{and when} && \omega t_1 = -\frac{\pi}{2}, \text{ we get } v_{1min} = v_o\sqrt{1-\frac{V_1}{V_o}}\end{aligned}\right] \qquad \text{...(7.4)}$$

Let T be the transit time inside the drift space and t_2 be the time at which electron reaches catcher grid, *i.e.*,
$$t_2 = t_1 + T \qquad \text{...(7.5)}$$

From Eq. (7.5), we get
$$\omega t_2 = \omega t_1 + \omega\, T \qquad \text{...(7.5a)}$$

where ωt_2 = Transit angle at catcher grid

ωt_1 = Transit angle when electrons leave buncher grid.

$$T = \frac{s}{v_1} = \frac{s}{v_o\sqrt{1+\frac{V_1}{V_o}\sin \omega t_1}} \qquad \text{...(7.6)}$$

where $\frac{s}{v_o}$ is transit time for centre of bunch electron.

∴ From Eq. (7.5 *a*) and (7.6)
$$\omega t_2 = \omega t_1 + \frac{\omega s}{v_o\sqrt{1+\frac{V_1}{V_o}\sin \omega t_1}} \qquad \text{...(7.7)}$$

or
$$\omega t_2 = \omega t_1 + \frac{\alpha}{\sqrt{1+\frac{V_1}{V_o}\sin \omega t_1}} \qquad \text{...(7.8)}$$

where $\frac{\omega s}{v_o} = \alpha$ is called transit angle for centre of bunch electron and $\omega t_2 - \omega t_1 =$ transit angle inside the drift space.

Power output at catcher grid. Let $V_2 \sin \omega t_2$ be voltage at catcher grids, hence energy given by an electron is equal to $-eV_2 \sin \omega t_2 = W'$.

(Negative sign indicates that energy is given by the electron.)

Average energy given by an electron to the field (per electron)

$$\therefore \quad W/\text{electron} = \frac{1}{2\pi}\int_{\omega t_1 = 0}^{2\pi} W'\, d(\omega t_1) \qquad \text{...(7.9)}$$

$$P_{av} = \frac{1}{2\pi}\int_0^{2\pi} (-eV_2 \sin \omega t_2)\, d\,(\omega t_1)$$

From Eq. (7.8) and using binominal equation, we get

$$P_{av} = -\frac{eV_2}{2\pi}\int_0^{2\pi} \sin\left[\omega t_1 + \alpha\left(1-\frac{V_1}{2V_o}\sin \omega t_1\right)\right] d\,(\omega t_1) \qquad \text{...(7.10)}$$

$$P_{av} = -eV_2 J_1(x) \sin \alpha \qquad \text{...(7.11)}$$

where
$$x = \frac{\alpha V_1}{2V_o}$$

and is a bunching parameter for the klystron, $J_1(x)$ = Bessel function of the first order.

Fig. 7.5 gives a graph between $J_1(x)$ and x.

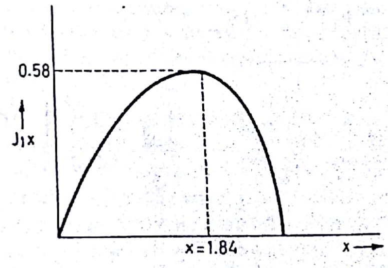

Fig. 7.5. Graph for Bessel function $J_1(x)$.

Let there be N electrons reaching the catcher.

∴ Energy transferred to the catcher/sec.

tuning is awkward ; therefore, two cavity klystrons are generally used in fixed frequency applications. When frequency is to be varied, the lower power, lower efficiency *reflex klystron* is used instead ; it has only one cavity resonator and therefore tuning is easy.

7.5. Reflex Klystron

A reflex klystron is a low power, low efficiency microwave oscillator, illustrated schematically in Fig. 7.6. It consists of an electron gun similar to that of a multicavity klystron, a filament surrounded by a cathode and a focussing electrode at the cathode potential. The suitably formed electron beam is accelerated towards the cavity, which has a high positive voltage applied to it and thus acts as an anode. After passing the gap in the cavity, electrons travel towards repeller electrode which is at a high negative potential.

The electrons never reach this electrode because of the negative field.

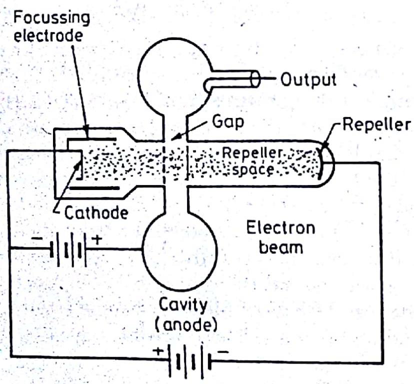

Fig. 7.6. Reflex klystron schematic.

The electrons are repelled back from midway of the repeller space by the repeller grid towards the anode ; if conditions are properly adjusted, then the returning electrons give more energy to the gap than they took from it on forward journey, and thus oscillations are sustained.

7.5.1. Operation. It is assumed here as also is the case with two cavity klystron oscillator that oscillations are capable of starting through noise or switching transients. In order to understand the operation it is advantageous to consider specific electrons, passing the gap for the first time at selected times. Here reference electron taken is y and it passes the gap without being affected by the voltage across it and travels towards to repeller, and is returned back to anode without touching the repeller. The fast electrons come nearer to the repeller than slow ones, and therefore take a longer time to return to the resonator gap than electrons which did not approach the repeller so closely.

The system is analogous to throwing stones upward (since the gravitational field of the earth is very similar to the field to which the electrons are subjected near the repeller) ; more forcefully a stone is thrown upward, longer it takes to come down again. Fig. 7.7 shows the Applegate diagram for a reflex klystron. It shows the path of reference electron y, rather the position of y at any instant in the repeller space ; its path of course is straight out and then straight back along the same line. Consider an electron x which passes the resonator gap (on its way out) slightly before the reference electron. Had there been no gap voltage, x would have returned before the reference electron. However, due to presence of RF voltage the electrons will be velocity modulated. Electron x, as seen is in fact accelerated due to the positive field available to it and so comes closer to the repeller as compared to reference electron y. As seen from Fig. 7.7, it is quite possible that y will catch up with electron x as they enter back into resonator gap. Similarly electron z leaves the gap slightly after the reference electron y and experiences a negative field which slows it ; therefore electron z does not reach as close to repeller compared to electron y, before it is returned back to resonator gap. There exists every possibility that electron z also catches up with electron y as it enters back into the gap. Thus all the three electrons x, y and z return back nearly at the same time into the resonator gap.

The system now becomes analogous to a 2 cavity klystron where velocity modulation is converted into current modulation after the electrons have left the gap on their outward journey. The bunching in reflex klystron is not as complete as in a multicavity klystron, because there are quite a few electrons arriving at the gap out of phase and contributing to the high noise and low efficiency of the device. However, bunching is sufficient between the bunching limits, to make operation possible.