UNIT-III

MICROWAVE TUBES

Two cavity klystron:

The two-cavity klystron is a widely used microwave amplifier operated by the principles of velocity and current modulation. All electrons injected from the cathode arrive at the first cavity with uniform velocity. Those electrons passing the first cavity gap at zeros of the gap voltage (or signal voltage) pass through with unchanged velocity; those passing through the positive half cycles of the gap voltage undergo an increase in velocity; those passing through the negative swings of the gap voltage undergo a decrease in velocity.

As a result of these actions, the electrons gradually bunch together as they travel down the drift space. The variation in electron velocity in the drift space is known as *velocity modulation.* The density of the electrons in the second cavity gap varies cyclically with time.

The electron beam contains an ac component and is said to be current-modulated. The maximum bunching should occur approximately midway between the second cavity grids during its retarding phase; thus the kinetic energy is transferred from the electrons to the field of the second cavity.

The electrons then emerge from the second cavity with reduced velocity and finally terminate at the collector. The charateristics of a two-cavity klystron amplifier are as follows:

1.Efficiency: about 40%.

2.Power output: average power (CW power) is up to 500 kW and pulsed power is up to 30 MW at 10 GHz.
3.Power gain: about 30 dB.

Reentrant Cavities

The coaxial cavity is similar to a coaxial line shorted at two ends and joined at the center by a capacitor. The input impedance to each shorted coaxial line is given by

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\,\ell n\frac{b}{a} \qquad \text{ohms} \qquad (9\text{-}2\text{-}1)$$

where *e* is the length of the coaxial line.

Substitution of Eq. (9-2-l) in (9-2-2) results in

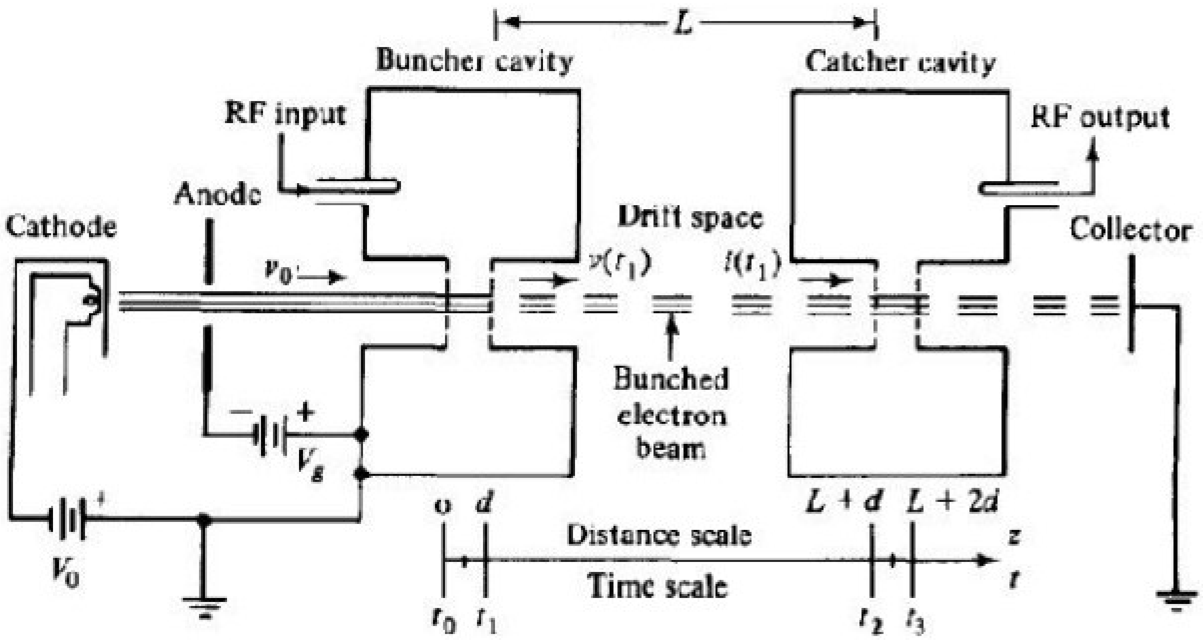


Figure 9-2-2 Two-cavity klystron amplifier.

$$L = \frac{2X_{in}}{\omega} = \frac{1}{\pi\omega}\sqrt{\frac{\mu}{\epsilon}}\,\ell n\frac{b}{a}\tan(\beta\ell) \qquad (9\text{-}2\text{-}4)$$

and the capacitance of the gap by

$$C_g = \frac{\epsilon\pi a^2}{d} \qquad (9\text{-}2\text{-}5)$$

The inductance of the cavity is given by

At resonance the inductive reactance of the two shorted coaxial lines in series is equal in magnitude to the capacitive reactance of the gap. That is, *wL* = 1/(wCg).

Thus where *v* = 1/yr;;; is the phase velocity in any medium

Velocity-Modulation Process

When electrons are first accelerated by the high de voltage *Vo* before entering the buncher grids, their velocity is uniform:

$$v_0 = \sqrt{\frac{2eV_0}{m}} = 0.593 \times 10^6 \sqrt{V_0} \qquad \text{m/s} \qquad (9\text{-}2\text{-}10)$$

In Eq. (9-2-10) it is assumed that electrons leave the cathode with zero velocity. When a microwave signal is applied to the input terminal, the gap voltage between the buncher grids appears as

$$V_s = V_1 \sin(\omega t) \qquad (9\text{-}2\text{-}11)$$

where V1 is the amplitude of the signal and V1 << *Vo* is assumed.

In order to find the modulated velocity in the buncher cavity in terms of either the entering time *to* or the exiting time t1 and the gap transit angle *88* as shown in Fig. 9-2-2 it is necessary to determine the average microwave voltage in the buncher gap as indicated in Fig. 9-2-6. Since V1 << *Vo* , the average transit time through the buncher gap distance *d* is

$$\tau \approx \frac{d}{v_0} = t_1 - t_0 \quad (9\text{-}2\text{-}12)$$

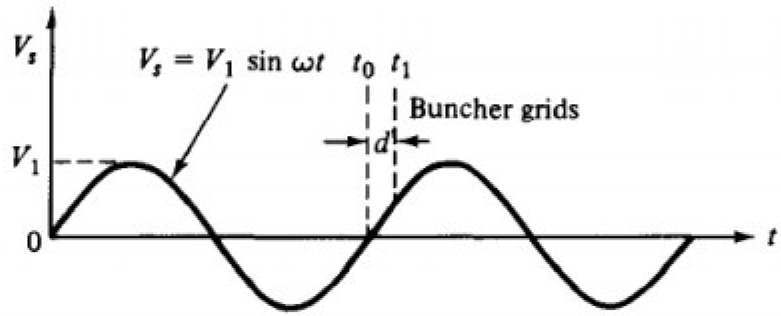


Figure 9-2-6 Signal voltage in the buncher gap.

The average gap transit angle can be expressed as

$$\theta_g = \omega\tau = \omega(t_1 - t_0) = \frac{\omega d}{v_0} \quad (9\text{-}2\text{-}13)$$

The average microwave voltage in the buncher gap can be found in the following way:

$$\begin{aligned}\langle V_s \rangle &= \frac{1}{\tau}\int_{t_0}^{t_1} V_1 \sin(\omega t)dt = -\frac{V_1}{\omega\tau}[\cos(\omega t_1) - \cos(\omega t_0)] \\ &= \frac{V_1}{\omega\tau}\left[\cos(\omega t_0) - \cos\left(\omega_0 + \frac{\omega d}{v_0}\right)\right] \quad (9\text{-}2\text{-}14)\end{aligned}$$

Let

$$\omega t_0 + \frac{\omega d}{2v_0} = \omega t_0 + \frac{\theta_g}{2} = A$$

and

$$\frac{\omega d}{2v_0} = \frac{\theta_g}{2} = B$$

Then using the trigonometric identity that cos $(A - B)$ − cos $(A + B)$ = 2 sin A sin B, Eq. (9-2-14) becomes

$$\langle V_s \rangle = V_1 \frac{\sin[\omega d/2v_0)]}{\omega d/(2v_0)} \sin\left(\omega t_0 + \frac{\omega d}{2v_0}\right) = V_1 \frac{\sin(\theta_g/2)}{\theta_g/2} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right) \tag{9-2-15}$$

It is defined as

$$\beta_i = \frac{\sin[\omega d/(2v_0)]}{\omega d/(2v_0)} = \frac{\sin(\theta_g/2)}{\theta_g/2} \tag{9-2-16}$$

Note that β_i is known as the *beam-coupling coefficient* of the input cavity gap (see Fig. 9-2-7).

It can be seen that increasing the gap transit angle *0g* decreases the coupling between the electron beam and the buncher cavity; that is, the velocity modulation of the beam for a given microwave signal is decreased. Immediately after velocity modulation, the exit velocity from the buncher gap is given by

$$v(t_1) = \sqrt{\frac{2e}{m}\left[V_0 + \beta_i V_1 \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right]}$$
$$= \sqrt{\frac{2e}{m} V_0 \left[1 + \frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right]} \qquad (9\text{-}2\text{-}17)$$

where the factor $\beta_i V_1/V_0$ is called the *depth of velocity modulation*.

Using binomial expansion under the assumption of

$$\beta_i V_1 \ll V_0 \qquad (9\text{-}2\text{-}18)$$

Eq. (9-2-17) becomes

$$v(t_1) = v_0\left[1 + \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right] \qquad (9\text{-}2\text{-}19)$$

Equation (9-2-19) is the equation of velocity modulation. Alternatively, the equation of velocity modulation can be given by

$$v(t_1) = v_0\left[1 + \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \qquad (9\text{-}2\text{-}20)$$

Bunching Process

Once the electrons leave the buncher cavity, they drift with a velocity given by Eq. (9-2-19) or (9-2-20) along in the field-free space between the two cavities. The effect of velocity modulation produces bunching of the electron beam-or current modulation.

The electrons that pass the buncher at $V_s = 0$ travel through with unchanged velocity v_o and become the bunching center. Those electrons that pass the buncher cavity during the positive half cycles of the microwave input voltage V_s travel faster than the electrons that passed the gap when $V_s = 0$. Those electrons that pass the buncher cavity during the negative half cycles of the voltage V_s travel slower than the electrons that passed the gap when $V_s = 0$. At a distance of *!:J..L* along the beam from the buncher cavity, the beam electrons have drifted into dense clusters. Figure 9-2-8 shows the trajectories of minimum, zero, and maximum electron acceleration.

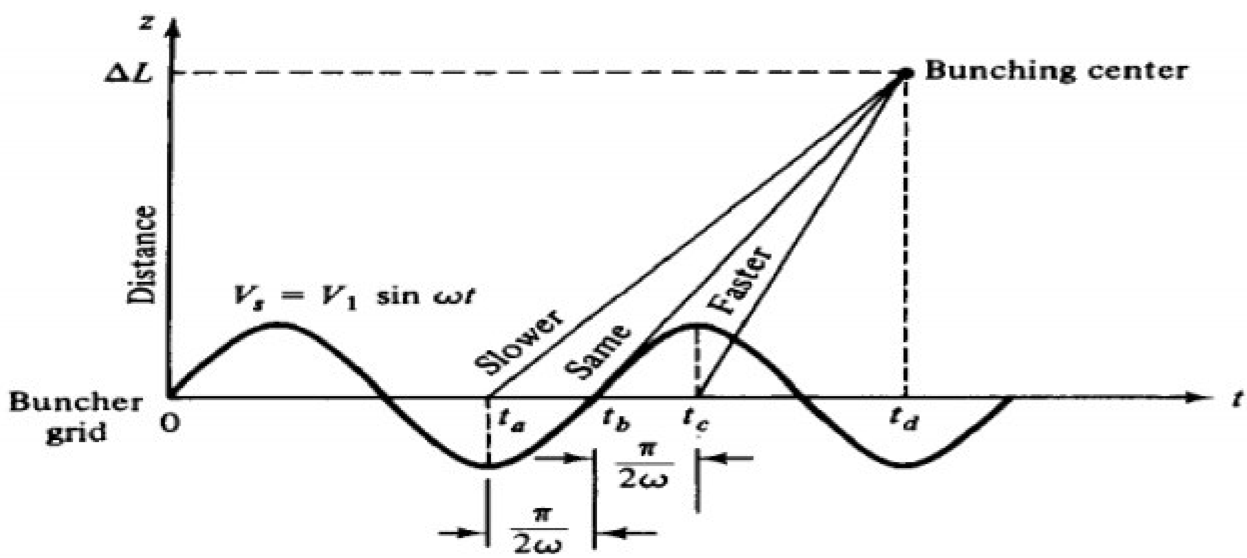


Figure 9-2-8 Bunching distance.

The distance from the buncher grid to the location of dense electron bunching for the electron at t_b is

$$\Delta L = v_0(t_d - t_b) \tag{9-2-21}$$

Similarly, the distances for the electrons at t_a and t_c are

$$\Delta L = v_{\min}(t_d - t_a) = v_{\min}\left(t_d - t_b + \frac{\pi}{2\omega}\right) \tag{9-2-22}$$

$$\Delta L = v_{\max}(t_d - t_c) = v_{\max}\left(t_d - t_b - \frac{\pi}{2\omega}\right) \tag{9-2-23}$$

From Eq. (9-2-19) or (9-2-20) the minimum and maximum velocities are

$$v_{\min} = v_0\left(1 - \frac{\beta_i V_1}{2V_0}\right) \tag{9-2-24}$$

$$v_{\max} = v_0\left(1 + \frac{\beta_i V_1}{2V_0}\right) \tag{9-2-25}$$

Substitution of Eqs. (9-2-24) and (9-2-25) in Eqs. (9-2-22) and (9-2-23), respectively, yields the distance

$$\Delta L = v_0(t_d - t_b) + \left[v_0\frac{\pi}{2\omega} - v_0\frac{\beta_i V_1}{2V_0}(t_d - t_b) - v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \tag{9-2-26}$$

and

$$\Delta L = v_0(t_d - t_b) + \left[-v_0\frac{\pi}{2\omega} + v_0\frac{\beta_i V_1}{2V_0}(t_d - t_b) + v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \tag{9-2-27}$$

The necessary condition for those electrons at t_a, t_b, and t_c to meet at the same distance ΔL is

$$v_0\frac{\pi}{2\omega} - v_0\frac{\beta_i V_1}{2V_0}(t_d - t_b) - v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega} = 0 \tag{9-2-28}$$

and

$$-v_0\frac{\pi}{2\omega} + v_0\frac{\beta_i V_1}{2V_0}(t_d - t_b) + v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega} = 0 \tag{9-2-29}$$

Consequently,

$$t_d - t_b \approx \frac{\pi V_0}{\omega \beta_i V_1} \tag{9-2-30}$$

and

$$\Delta L = v_0 \frac{\pi V_0}{\omega \beta_i V_1} \tag{9-2-31}$$

$$T = t_2 - t_1 = \frac{L}{v(t_1)} = T_0\left[1 - \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \tag{9-2-32}$$

where the binomial expansion of $(1 + x)^{-1}$ for $|x| \ll 1$ has been replaced and $T_0 = L/v_0$ is the dc transit time. In terms of radians the preceding expression can be written

$$\omega T = \omega t_2 - \omega t_1 = \theta_0 - X \sin\left(\omega t_1 - \frac{\theta_g}{2}\right) \tag{9-2-33}$$

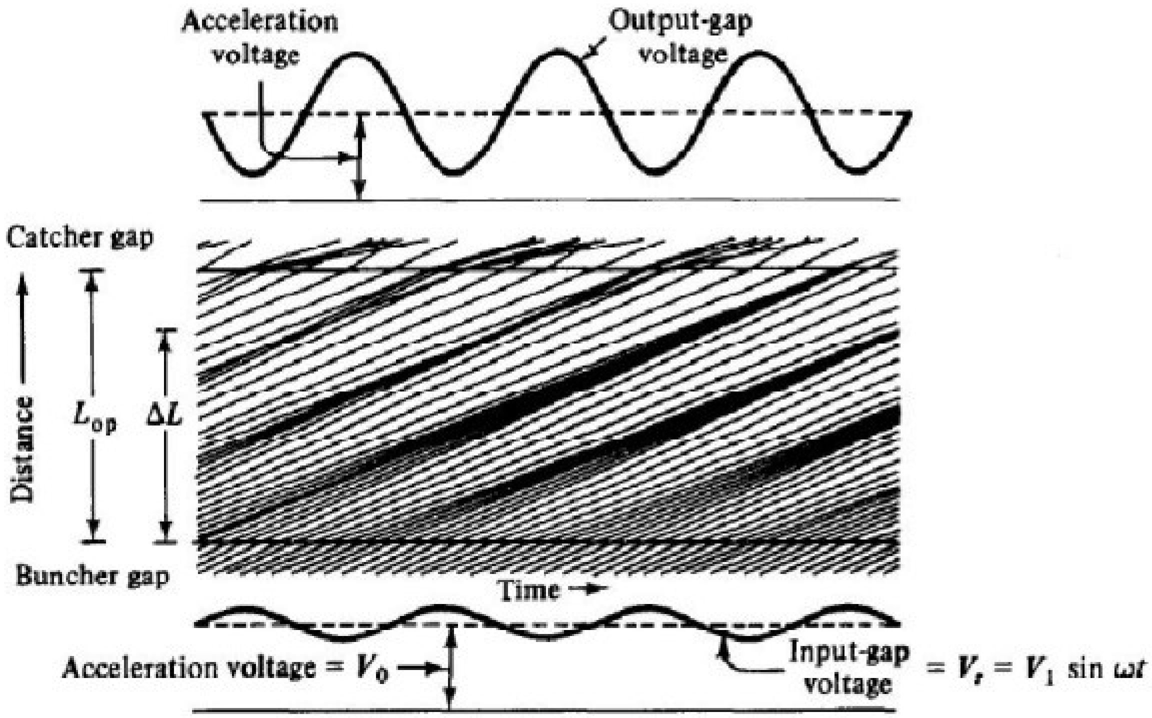


Figure 9-2-9 Applegate diagram.

where

$$\theta_0 = \frac{\omega L}{v_0} = 2\pi N \tag{9-2-34}$$

is the dc transit angle between cavities, N is the number of electron transit cycles in the drift space, and

$$X \equiv \frac{\beta_i V_1}{2V_0} \theta_0 \tag{9-2-35}$$

where I_0 is the dc current. From the principle of conservation of charges this same amount of charge dQ_0 also passes the catcher at a later time interval dt_2. Hence

$$I_0|dt_0| = i_2|dt_2| \tag{9-2-37}$$

where the absolute value signs are necessary because a negative value of the time ratio would indicate a negative current. Current i_2 is the current at the catcher gap. Rewriting Eq. (9-2-32) in terms of Eq. (9-2-19) yields

$$t_2 = t_0 + \tau + T_0\left[1 - \frac{\beta_i V_1}{2V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2}\right)\right] \tag{9-2-38}$$

Alternatively,

$$\omega t_2 - \left(\theta_0 + \frac{\theta_g}{2}\right) = \left(\omega t_0 + \frac{\theta_g}{2}\right) - X \sin\left(\omega t_0 + \frac{\theta_g}{2}\right) \tag{9-2-39}$$

where $(\omega t_0 + \theta_g/2)$ is the buncher cavity departure angle and $\omega t_2 - (\theta_0 + \theta_g/2)$ is the catcher cavity arrival angle. Figure 9-2-10 shows the curves for the catcher cav-

Differentiation of Eq. (9-2-38) with respect to t_0 results in

$$dt_2 = dt_0\left[1 - X\cos\left(\omega t_0 + \frac{\theta_g}{2}\right)\right] \tag{9-2-40}$$

The current arriving at the catcher cavity is then given as

$$i_2(t_0) = \frac{I_0}{1 - X\cos(\omega t_0 + \theta_g/2)} \tag{9-2-41}$$

In terms of t_2 the current is

$$i_2(t_2) = \frac{I_0}{1 - X\cos(\omega t_2 - \theta_0 - \theta_g/2)} \tag{9-2-42}$$

The optimum distance L at which the maximum fundamental component of current occurs is computed from Eqs. (9-2-34), (9-2-35), and (9-2-54) as

$$L_{\text{optimum}} = \frac{3.682 v_0 V_0}{\omega \beta_i V_1} \tag{9-2-55}$$

REFLEX KLYSTRON

If a fraction of the output power is fed back to the input cavity and if the loop gain has a magnitude of unity with a phase shift of multiple 27T, the klystron will oscillate. However, a two-cavity klystron oscillator is usually not constructed because, when the oscillation frequency is varied, the resonant frequency of each cavity and the feedback path phase shift must be readjusted for a positive feedback.

The reflex klystron is a single-cavity klystron that overcomes the disadvantages of the twocavity klystron oscillator. It is a low-power generator of 10 to 500-mW output at a frequency range of I to 25 GHz. The efficiency is about 20 to 30%. This type is widely used in the laboratory for microwave measurements and in microwave receivers as local oscillators in commercial, military, and airborne Doppler radars as well as missiles.

The theory of the two-cavity klystron can be applied to the nalysis of the reflex klystron with slight modification. A schematic diagram of the reflex klystron is shown in Fig. 9-4-1.

The electron beam injected from the cathode is first velocity-modulated by the cavity-gap voltage. Some electrons accelerated by the accelerating field enter therepeller space with greater velocity than those with unchanged velocity. Some electrons decelerated by the retarding field enter the repeller region with less velocity.

All electrons turned around by the repeller voltage then pass through the cavity gap in bunches that occur once per cycle. On their return journey the bunched electrons pass through the gap during the retarding phase of the alternating field and give up their kinetic energy to the electromagnetic energy of the field in the cavity. Oscillator output energy is then taken from the cavity. The electrons are finally collected by the walls of the cavity or other grounded metal parts of the tube. Figure 9-4-2 shows an Applegate diagram for the 1~ mode of a reflex klystron.

Velocity Modulation

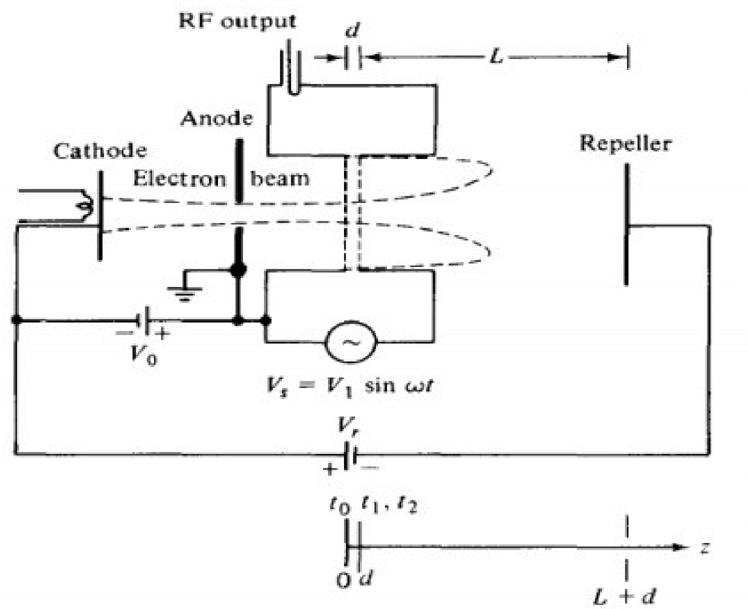
The analysis of a reflex klystron is similar to that of a two-cavity klystron. For simplicity, the effect of space-charge forces on the electron motion will again be neglected. The electron entering the cavity gap from the cathode at $z = 0$ and time *to* is assumed to have uniform velocity

This expression is identical to Eq. (9-2-17), for the problems up to this point are identical to those of a two-cavity klystron amplifier. The same electron is forced back to the cavity $z = d$ and time *tz* by the retarding electric field *E,* which is given by

This retarding field *E* is assumed to be constant in the *z* direction. The force equation for one electron in the repeller region is

where E = - VY is used in the *z* direction only, *Yr* is the magnitude of the repeller voltage, and I Yt sin *wt* I ~ (Yr + Yo) is assumed. Integration of Eq. (9-4-4) twice yields

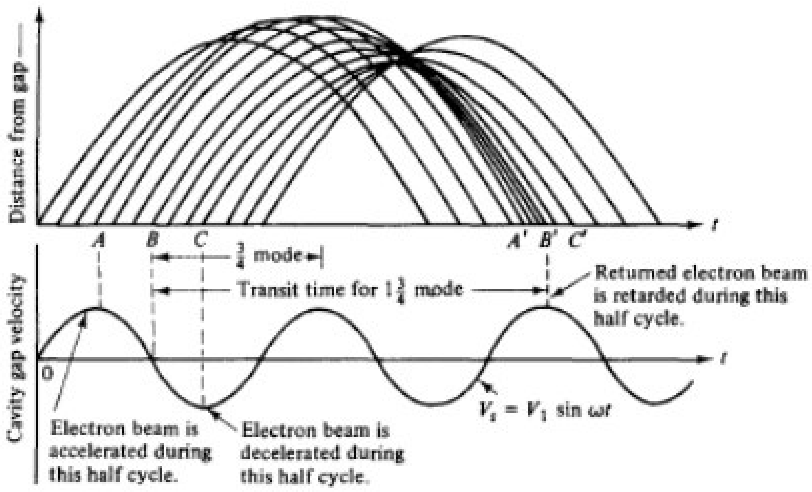
$$\frac{dz}{dt} = \frac{-e(V_r + V_0)}{mL} \int_{t1}^{t} dt = \frac{-e(V_r + V_0)}{mL}(t - t_1) + K_1 \qquad (9\text{-}4\text{-}5)$$



t0 time for electron entering cavity gap at *z* = 0

t 1 time for same electron leaving cavity gap at *z* = *d* time for same electron returned by retarding field

$z = d$ and collected on walls of cavity



at $t = t_1$, $dz/dt = v(t_1) = K_1$; then

$$z = \frac{-e(V_r + V_0)}{mL} \int_{t_1}^{t} (t - t_1)\, dt + v(t_1) \int_{t_1}^{t} dt$$

$$z = \frac{-e(V_r + V_0)}{2mL} (t - t_1)^2 + v(t_1)(t - t_1) + K_2$$

at $t = t_1$, $z = d = K_2$; then

$$z = \frac{-e(V_r + V_0)}{2mL} (t - t_1)^2 + v(t_1)(t - t_1) + d \qquad (9\text{-}4\text{-}6)$$

On the assumption that the electron leaves the cavity gap at $z = d$ and time t_1 with a velocity of $v(t_1)$ and returns to the gap at $z = d$ and time t_2, then, at $t = t_2$, $z = d$,

$$0 = \frac{-e(V_r + V_0)}{2mL}(t_2 - t_1)^2 + v(t_1)(t_2 - t_1)$$

The round-trip transit time in the repeller region is given by

$$T' = t_2 - t_1 = \frac{2mL}{e(V_r + V_0)}v(t_1) = T_0'\left[1 + \frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \qquad (9\text{-}4\text{-}7)$$

where

$$T_0' = \frac{2mLv_0}{e(V_r + V_0)} \qquad (9\text{-}4\text{-}8)$$

is the round-trip dc transit time of the center-of-the-bunch electron.

Multiplication of Eq. (9-4-7) through by a radian frequency results in

$$\omega(t_2 - t_1) = \theta_0' + X'\sin\left(\omega t_1 - \frac{\theta_g}{2}\right) \qquad (9\text{-}4\text{-}9)$$

where

$$\theta_0' = \omega T_0' \qquad (9\text{-}4\text{-}10)$$

s the round-trip dc transit angle of the center-of-the-bunch electron and

$$X' = \frac{\beta_i V_1}{2V_0}\theta_0' \qquad (9\text{-}4\text{-}11)$$

s the bunching parameter of the reflex klystron oscillator.

TRAVELING WAVE TUBE

Since Kompfner invented the helix traveling-wave tube (TWT) in 1944 , its basic circuit has changed little. For broadband applications, the helix TWTs are almost exclusively used, whereas for high-average-power purposes, such as radar transmitters, the coupled-cavity TWTs are commonly used.

In previous sections klystrons and reflex klystrons were analyzed in some detail. Before starting to describe the TWT, it seems appropriate to compare the basic operating principles of both the TWT and the klystron. In the case of the TWT, the microwave circuit is nonresonant and the wave propagates with the same speed as the electrons in the beam. The initial effect on the beam is a small amount of velocity modulation caused by the weak electric fields associated with the traveling wave.

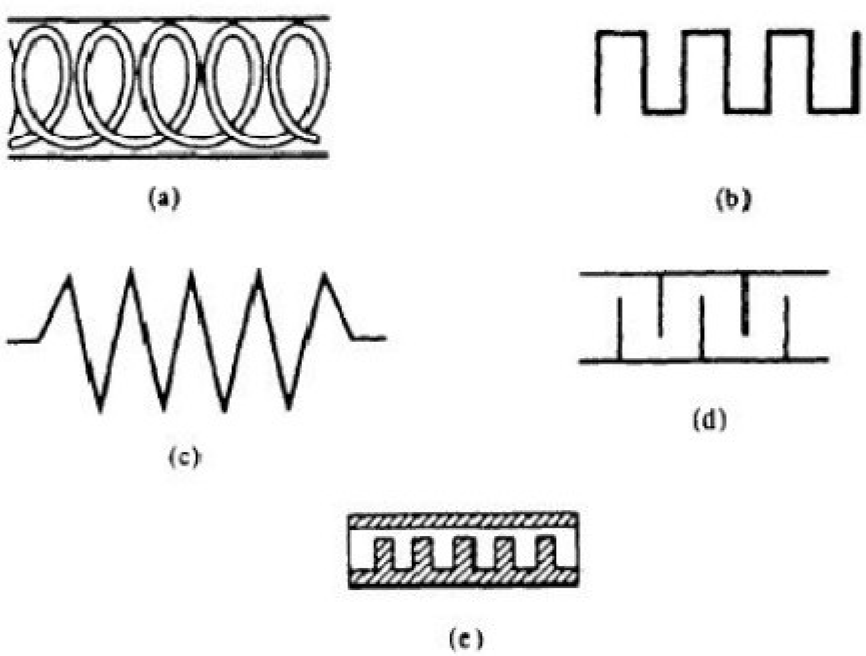
Just as in the klystron, this velocity modulation later translates to current modulation, which then induces an RF current in the circuit, causing amplification. However, there are some major differences between the TWT and the klystron:

The interaction of electron beam and RF field in the TWT is continuous over the entire length of the circuit, but the interaction in the klystron occurs only at the gaps of a few resonant cavities.

The wave in the TWT is a propagating wave; the wave in the klystron is not.

In the coupled-cavity TWT there is a coupling effect between the cavities, whereas each cavity in the klystron operates independently.

As the operating frequency is increased, both the inductance and capacitance of the resonant circuit must be decreased in order to maintain resonance at the operating frequency. Because the gain-bandwidth product is limited by the resonant circuit, the ordinary resonator cannot generate a large output. Several nonresonant periodic circuits or slow-wave structures (see Fig. 9-5-2) are designed for producing large gain over a wide bandwidth.



Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity in a certain direction so that the electron beam and the signal wave can interact. The phase velocity of a wave in ordinary waveguides is greater than the velocity of light in a vacuum.

In the operation of traveling-wave and magnetron-type devices, the electron beam must keep in step with the microwave signal. Since the electron beam can be accelerated only to velocities that are about a fraction of the velocity of light, a slow-wave structure must be incorporated in the microwave devices so that the phase velocity of the microwave signal can keep pace with that of the electron beam for effective interactions. Several types of slow-wave structures are shown in figure.

$$\frac{v_p}{c} = \frac{p}{\sqrt{p^2 + (\pi d)^2}} = \sin \psi$$