REFLEX KLYSTRONS

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 2π, 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 two-cavity klystron oscillator. It is a low-power generator of 10 to 500-mW output at a frequency range of 1 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 analysis 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 the repeller 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 $1\frac{3}{4}$ mode of a reflex klystron.

9-4-1 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 t_0 is assumed to have uniform velocity

$$v_0 = 0.593 \times 10^6 \sqrt{V_0} \tag{9-4-1}$$

The same electron leaves the cavity gap at $z = d$ at time t_1 with velocity

$$v(t_1) = v_0\left[1 + \frac{\beta_1 V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \tag{9-4-2}$$

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 t_2 by the retarding electric field E, which is given by

$$E = \frac{V_r + V_0 + V_1 \sin(\omega t)}{L} \tag{9-4-3}$$

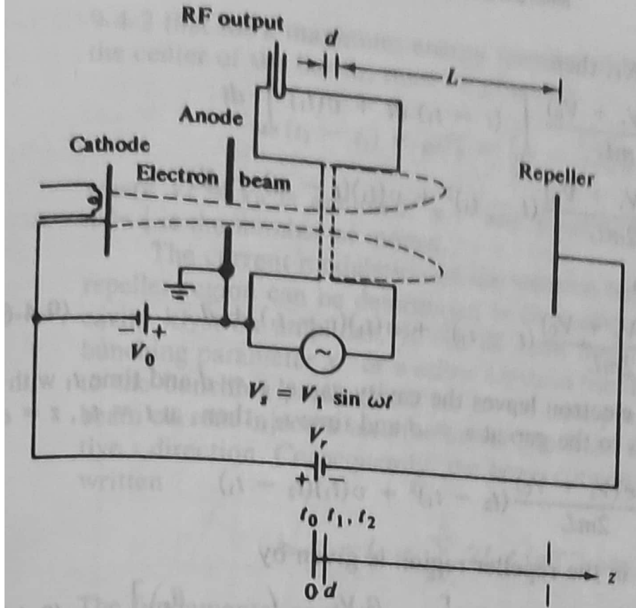
This retarding field E is assumed to be constant in the z direction. The force equation for one electron in the repeller region is

$$m\frac{d^2z}{dt^2} = -eE = -e\frac{V_r + V_0}{L} \tag{9-4-4}$$

where $\mathbf{E} = -\nabla V$ is used in the z direction only, V_r is the magnitude of the repeller voltage, and $|V_1 \sin \omega t| \ll (V_r + V_0)$ is assumed.

Integration of Eq. (9-4-4) twice yields

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



t_0 = time for electron entering cavity gap at $z = 0$
t_1 = time for same electron leaving cavity gap at $z = d$
t_2 = time for same electron returned by retarding field $z = d$ and collected on walls of cavity

Figure 9-4-1 Schematic diagram of a reflex klystron.

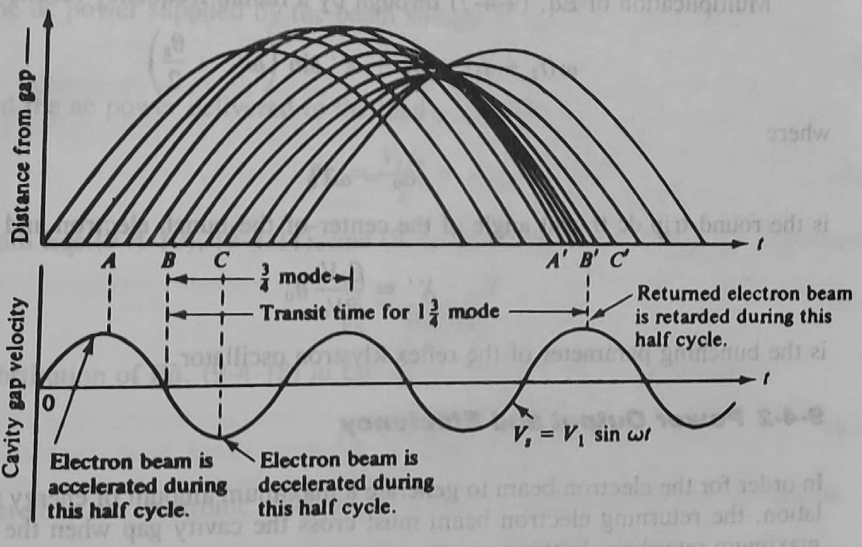


Figure 9-4-2 Applegate diagram with gap voltage for a reflex klystron.

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

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

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

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

where

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

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

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

where

$$\theta_0' = \omega T_0' \tag{9-4-10}$$

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

$$X' \equiv \frac{\beta_i V_1}{2V_0}\theta_0' \tag{9-4-11}$$

is the bunching parameter of the reflex klystron oscillator.

9-4-2 Power Output and Efficiency

In order for the electron beam to generate a maximum amount of energy to the oscillation, the returning electron beam must cross the cavity gap when the gap field is maximum retarding. In this way, a maximum amount of kinetic energy can be transferred from the returning electrons to the cavity walls. It can be seen from Fig.

9-4-2 that for a maximum energy transfer, the round-trip transit angle, referring to the center of the bunch, must be given by

$$\omega(t_2 - t_1) = \omega T_0' = \left(n - \frac{1}{4}\right)2\pi = N2\pi = 2\pi n - \frac{\pi}{2} \tag{9-4-12}$$

where $V_1 \ll V_0$ is assumed, n = any positive integer for cycle number, and $N = n - \frac{1}{4}$ is the number of modes.

The current modulation of the electron beam as it reenters the cavity from the repeller region can be determined in the same manner as in Section 9-2 for a two-cavity klystron amplifier. It can be seen from Eqs. (9-2-30) and (9-4-9) that the bunching parameter X' of a reflex klystron oscillator has a negative sign with respect to the bunching parameter X of a two-cavity klystron amplifier. Furthermore, the beam current injected into the cavity gap from the repeller region flows in the negative z direction. Consequently, the beam current of a reflex klystron oscillator can be written

$$i_{2t} = -I_0 - \sum_{n=1}^{\infty} 2I_0 J_n(nX') \cos[n(\omega t_2 - \theta_0' - \theta_g)] \tag{9-4-13}$$

The fundamental component of the current induced in the cavity by the modulated electron beam is given by

$$i_2 = -\beta_i I_2 = 2I_0\beta_i J_1(X') \cos(\omega t_2 - \theta_0') \tag{9-4-14}$$

in which θ_g has been neglected as a small quantity compared with θ_0'. The magnitude of the fundamental component is

$$I_2 = 2I_0\beta_i J_1(X') \tag{9-4-15}$$

The dc power supplied by the beam voltage V_0 is

$$P_{dc} = V_0 I_0 \tag{9-4-16}$$

and the ac power delivered to the load is given by

$$P_{ac} = \frac{V_1 I_2}{2} = V_1 I_0 \beta_i J_1(X') \tag{9-4-17}$$

From Eqs.(9-4-10), (9-4-11), and (9-4-12) the ratio of V_1 over V_0 is expressed by

$$\frac{V_1}{V_0} = \frac{2X'}{\beta_i(2\pi n - \pi/2)} \tag{9-4-18}$$

Substitution of Eq. (9-4-18) in Eq. (9-4-17) yields the power output as

$$P_{ac} = \frac{2V_0 I_0 X' J_1(X')}{2\pi n - \pi/2} \tag{9-4-19}$$

Therefore the electronic efficiency of a reflex klystron oscillator is defined as

$$\text{Efficiency} \equiv \frac{P_{ac}}{P_{dc}} = \frac{2X' J_1(X')}{2\pi n - \pi/2} \tag{9-4-20}$$

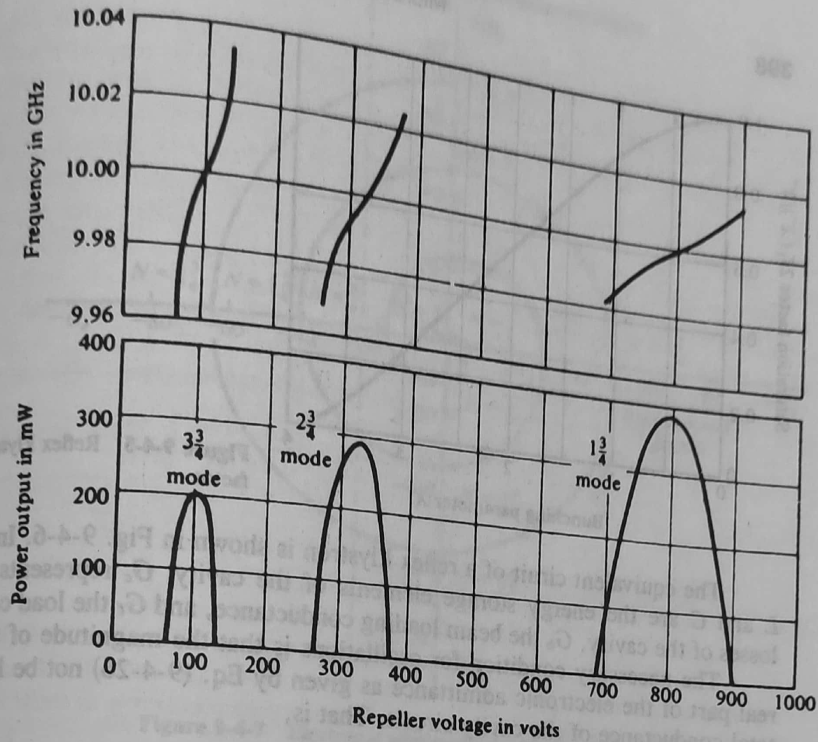


Figure 9-4-4 Power output and frequency characteristics of a reflex klystron.

9-4-3 Electronic Admittance

From Eq. (9-4-14) the induced current can be written in phasor form as

$$i_2 = 2I_0\beta_i J_1(X')e^{-j\theta_0'} \tag{9-4-24}$$

The voltage across the gap at time t_2 can also be written in phasor form:

$$V_2 = V_1 e^{-j\pi/2} \tag{9-4-25}$$

The ratio of i_2 to V_2 is defined as the electronic admittance of the reflex klystron. That is,

$$Y_e = \frac{I_0}{V_0}\frac{\beta_i^2\theta_0'}{2}\frac{2J_1(X')}{X'}e^{j(\pi/2-\theta_0')} \tag{9-4-26}$$

The amplitude of the phasor admittance indicates that the electronic admittance is a function of the dc beam admittance, the dc transit angle, and the second transit of the electron beam through the cavity gap. It is evident that the electronic admittance is nonlinear, since it is proportional to the factor $2J_1(X')/X'$, and X' is proportional to the signal voltage. This factor of proportionality is shown in Fig. 9-4-5. When the signal voltage goes to zero, the factor approaches unity.

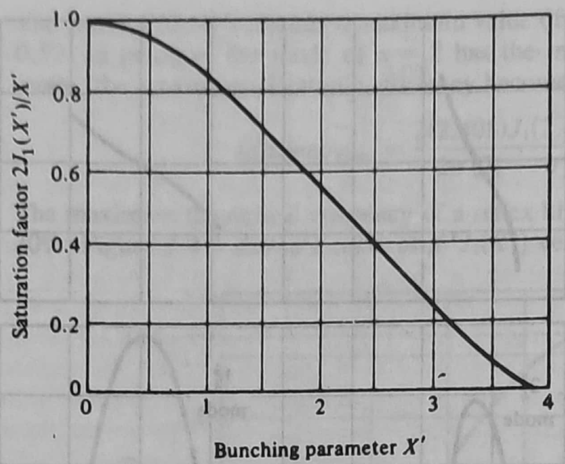


Figure 9-4-5 Reflex klystron saturation factor.

The equivalent ciruit of a reflex klystron is shown in Fig. 9-4-6. In this circuit L and C are the energy storage elements of the cavity; G_c represents the copper losses of the cavity, G_b the beam loading conductance, and G_ℓ the load conductance.

The necessary condition for oscillations is that the magnitude of the negative real part of the electronic admittance as given by Eq. (9-4-26) not be less than the total conductance of the cavity circuit. That is,

$$|-G_e| \geq G \tag{9-4-27}$$

where $G = G_c + G_b + G_\ell = 1/R_{sh}$ and R_{sh} is the effective shunt resistance.

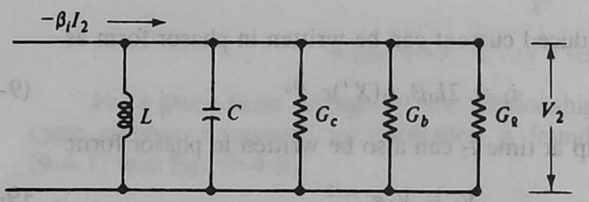


Figure 9-4-6 Equivalent circuit of a reflex klystron.

Equation (9-4-26) can be rewritten in rectangular form:

$$Y_e = G_e + jB_e \tag{9-4-28}$$

Since the electronic admittance shown in Eq. (9-4-26) is in exponential form, its phase is $\pi/2$ when θ_0' is zero. The rectangular plot of the electron admittance Y_e is a spiral (see Fig. 9-4-7). Any value of θ_0' for which the spiral lies in the area to the left of line $(-G - jB)$ will yield oscillation. That is,

$$\theta_0' = \left(n - \frac{1}{4}\right)2\pi = N\,2\pi \tag{9-4-29}$$

where N is the mode number as indicated in the plot, the phenomenon verifies the early analysis.

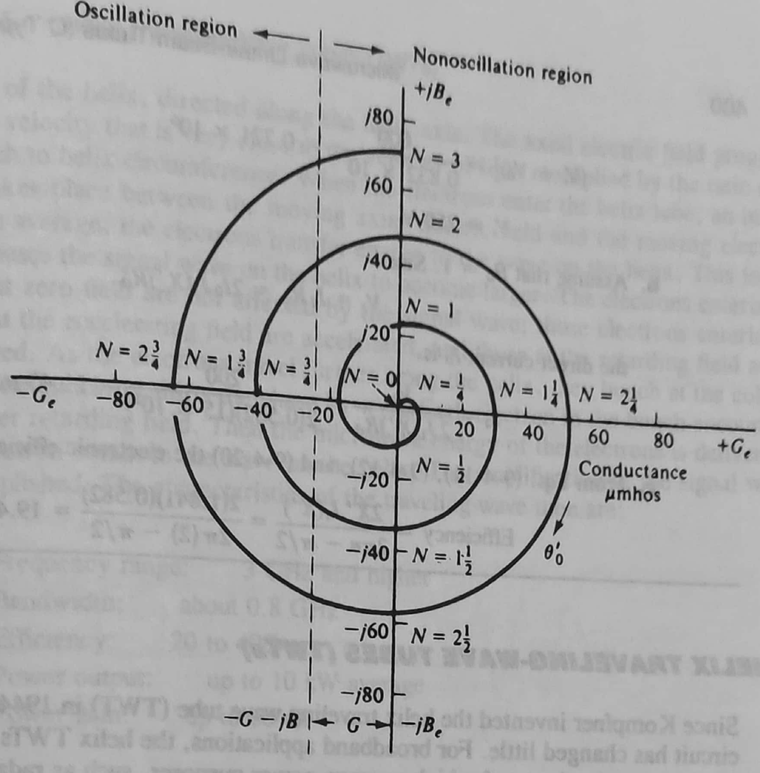


Figure 9-4-7 Electronic admittance spiral of a reflex klystron.

Example 9-4-1: Reflex Klystron

A reflex klystron operates under the following conditions:

$$V_0 = 600 \text{ V} \qquad L = 1 \text{ mm}$$

$$R_{sh} = 15\text{k}\Omega \qquad \frac{e}{m} = 1.759 \times 10^{11} \text{ (MKS system)}$$

$$f_r = 9 \text{ GHz}$$

The tube is oscillating at f_r at the peak of the $n = 2$ mode or $1\frac{3}{4}$ mode. Assume that the transit time through the gap and beam loading can be neglected.

a. Find the value of the repeller voltage V_r.

b. Find the direct current necessary to give a microwave gap voltage of 200 V.

c. What is the electronic efficiency under this condition?

Solution

a. From Eq. (9-4-22) we obtain

$$\frac{V_0}{(V_r + V_0)^2} = \left(\frac{e}{m}\right)\frac{(2\pi n - \pi/2)^2}{8\omega^2 L^2}$$

$$= (1.759 \times 10^{11})\frac{(2\pi\, 2 - \pi/2)^2}{8(2\pi \times 9 \times 10^9)^2(10^{-3})^2} = 0.832 \times 10^{-3}$$