MICROWAVE AND OPTICAL COMMUNICATIONS

(23EC701)

LECTURE NOTES

IV B.TECH- I SEM ECE

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UNIT-I

MICROWAVE TUBES

Limitations and losses of conventional Tubes at Microwave Frequencies

Conventional vacuum triodes, tetrodes and pentodes are less useful signal sources at frequencies above 1 G Hz because of

- lead inductance
- Inter-electrode capacitance effects,
- Transit angle effects
- Gain bandwidth product limitations.
- Power losses

Lead inductance and inter-electrode capacitance effects

At frequencies above 1 GHz conventional vacuum tubes are impaired by parasitic circuit reactance because the circuit capacitances between tube electrodes and the circuit inductance of the lead wire are too large for a microwave resonant circuit. Further as the frequency increases the real part of the input admittance may be large enough to cause a serious over load of the input circuit and thereby reduce the operating efficiency of the tube.

Transit angle effects

Another limitation in the application of conventional tubes at microwave frequencies is the electron transit angle between electrodes. The electron transit angle is defines as

$$\Theta_g = \omega \quad = \frac{\omega d}{v_v}$$

Where $= \frac{d}{v_v}$ is the transit time across the gap d = separation between cathode and grid

v_v = Velocity of the electron 0.593 x $10^5 \sqrt{v_v}$

V_o = DC voltage

When frequencies are below microwave range, the transit angle is negligible. At microwave frequencies, however the transit time is large compared to the period of the microwave signal, and the potential between the cathode and the grid may alternate from 10 to 100 times during the electron transit. 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 oscillate back and forth in the cathode-grid space or return to the cathode. The overall result of transit angle effect is to reduce the operating efficiency of the vacuum tube. The degenerate effect becomes more serious when frequencies are well above 1 GHz.

Gain bandwidth product limitations

The gain-bandwidth product is independent of frequency. For a given tube, a higher gain can be achieved only at the expense of a narrower bandwidth. This restriction is applicable to a resonant circuit only. In microwave devices either reentrant cavities or slow-wave structures are used to obtain a possible overall high gain over a bandwidth.

Power losses

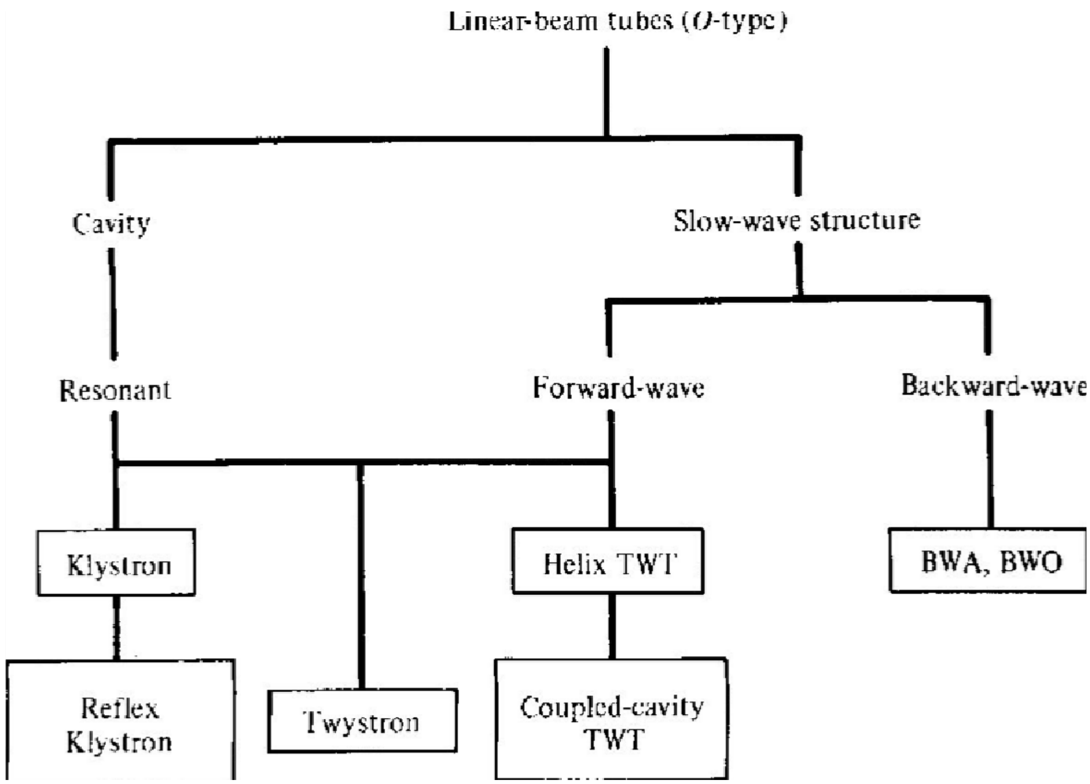
The use of conventional tubes at higher frequencies also increases in power losses resulting from skin effect, I^2R losses resulting from capacitance charging currents, losses due to radiation from the circuit and dielectric losses.

Classification of Microwave tubes.

Microwave Tubes

O-Type Tubes
(Linear beam tubes)

M-Type Tubes
(Cross field tubes)


Linear-beam tubes (O-type)
Cavity
Slow-wave structure
Resonant
Forward-wave
Backward-wave
Klystron
Helix TWT
BWA, BWO
Reflex Klystron
Twystron
Coupled-cavity TWT

Energy Transfer Mechanism

In most of the microwave tubes, the signal is placed in a cavity gap and electrons are forced to cross the gap at time when they face maximum opposition. Crosssing the gap under opposition lead to transfer of energy to the cavity gap signal. When the gap voltage is sinusoidal time-varying and the charge corssing is continuous and uniform, which is usually the case, no net transfer of energy takes place between cavity and the charge crossing the gap. It is because the energy transfer is equal and opposite in direction during a half cycle when compalred to previous half cycle resulting in no net transfer of energy in a cycle. To have net energy transfer, preferabley maximum, from electron beam to gap signal voltage the disributed charge is compressed into a thin sheet or bunch, so that it requires less time to cross the gap and it is arranged such hat the bunch corssing is at peak gap voltage so that the bunch faces maximum opposition and retardation from the signal voltage.

When the gap voltage is simusoidal and bunch corssing is at a uniform and constant rate, for maximum unidirectional flow of energy, there is only one instant, either at positive peak or negative peak, for the bunch to cross the gap. The bunch crossing hence mus be once per cycle of the gap voltage. In cse of bunch corssing at a uniform rate of ***f***, transfer of maximum energy can take place only with a a component of grid gap field whose frequency is also ***f***. Other components of the grid gap voltge like 2***f***, 4***f***, 8***f***, ets., do not involve in the energy transfer, whereas the components 3***f***, 5***f***, 6***f***, etc., and ***f***/2, ***f***/3. ***f***/4, etc., the transfered amount of energy is negligible.

Two Cavity Klystron

The two-cavity klystron is a widely used **microwave amplifier** operated by the principles of velocity and current modulatin. It consists of an elctron gun, focussing and accelerating grids, two identical cavities separated by a distance and at the far end a gounded collector plaate. The elctron gun emits electrons from the surace of its cathode and then they are focussed into a bearm. Using a dc accelerating positive voltage the beam is accelerated to high velocities.

Characteristics of two cavity klystron

Efficiency:	about 40%
Power output in CW mode:	upto 500 kW at 10 GHz
Power output in Pusled mode:	upto 30 MW at 10 GHz
Power gain:	about 30 dB

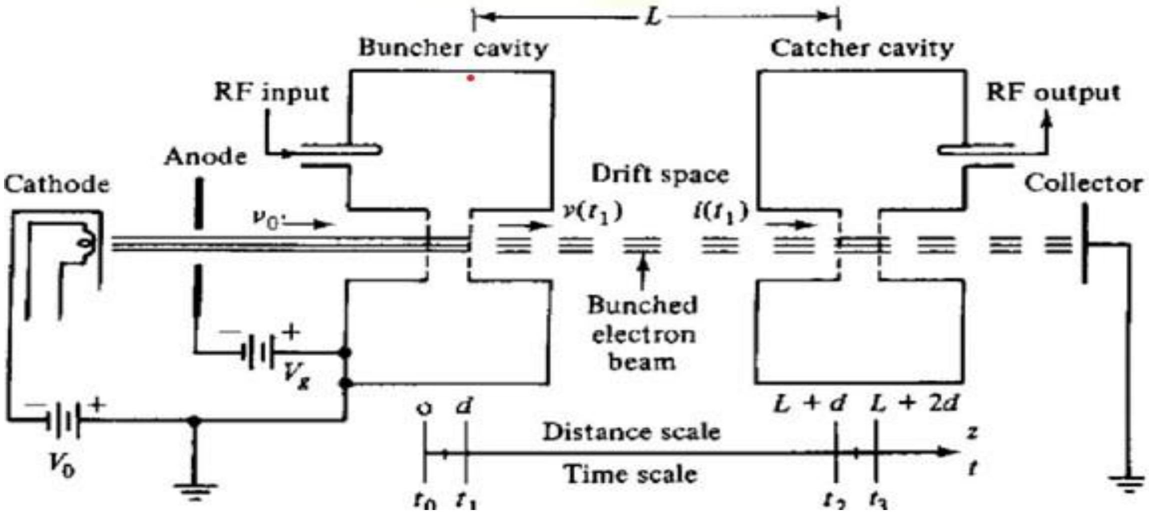


Fig 5.1 Schematic diagram of two cavity klystron

Components of two cavity klystron

1. **Cathode:** Source of electrons
2. **Anode:** for formation of electron beam
3. **Bucher Cavity:** A reentrat type resonator cavity which is kept at a +ve voltage of V_o w.r.t. cathode to effect acceleration of electrons. RF input voltage of **V_1 Sin *ωt*** is applied to buncher cavity.
4. **Catcher cavity:** Similar to buncher cavity. The amplified output signal **V_2 Sin *ωt*** is obtained from this cavity.
5. **Collector:** The elctrons after transfer of enerty to catcher cavity are collected by the collector.

Let us define varous parameters used in the description and operation of two cavity klystron.

V_o = DC voltage between cathode and buncher cavity.

V_1 = Amplitude of input RF signal, **$V_1 << V_o$**

ω = 2πf = Input signal angular frequency. It is also equal to resonant frequency of both the cavities.

V_o = Uniform velocity of electrons between cathode and buncher cavity.

t_o = Time at which electrons enter the buncher cavity

t_1 = Time at which electrons leave the buncher cavity

 = Transit time of electrons in the buncher cavity = $t_1 - t_o$

θ_g = Angle /Phase vaiation of input signal during the tansit time = ωŤ

β = Beam Coupling Coefficient of the buncher / Catcher Cavity

When the electrons enter the buncher cavity with uniform velocity „ v_0 ‟ interact with the field due to input RF signal $V_1 \sin \omega t$. The time varying field in the cavity cause the electrons to accelerate or decelerate and there by electrons undergo velocity modulation.

Let **v**(t_1) = Velocity of electrons at t= t_1 at the output of buncher cavity

This is a time varying quantity

Refer fig-5.3 for velocity modulation of electrons

Let d = cavity with of buncher / catcher cavity

L = spacing between buncher and catcher cavities

* „L‟ is the design parameter for optimum performance of the klystron amplifier

t_2 = Time at which electrons enter the catcher cavity

t_3= Time at which electrons leave the catcher cavity

d ● t_0

v_o t_1 (5.2)

Because $V_1 << V_0$

Evaluation of *v*(t_1)

***v*(t_1)** is the instantaneous velocity of electrons which is a time varying quantity and primarily depends upon the average voltage in the gap during the time „ ‟ i.e. during the time period (transit) the electrons are influenced by the field.

V_{avg} = Average voltage in the gap during time „ ‟

$$V_{avg} = \frac{1}{\tau}\int_{t_0}^{t_1} V_1 \sin \omega t \; dt$$

$$= \frac{-V_1}{\omega\tau}\left[\cos \omega t\right]_{t_0}^{t_1}$$

$$V_{avg} = \frac{-V_1}{\omega\tau}\left[\cos \omega t_1 - \cos \omega t_0\right] = V_{avg} = \frac{V_1}{\omega\tau}\left[\cos \omega t_o - \cos \omega t_1\right]$$

Where $\tau = t_1 - t_0$

$$t_1 = t_0 + \tau = t_0 + \frac{d}{v_o}$$

$$V_{avg} = \frac{V_1}{\omega\tau}\left[\cos \omega t_0 - \cos\left(\omega t_0 + \frac{\omega d}{v_0}\right)\right]$$

Where $\theta_g = \omega\tau = \frac{\omega d}{v_0}$

$$V_{avg} = \frac{V_1}{\omega\tau}\left[\cos \omega t_0 - \cos(\omega t_0 + \theta_g)\right]$$

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

and $B = \frac{\theta_g}{2}$

Since $\cos(A-B) - \cos(A+B) = 2 \sin A \sin B$

$$V_{avg} = V_1 \left\{ \frac{\sin(\omega d / 2v_0)}{\omega d / 2v_0} \right\} \sin\left(\omega t_0 + \frac{\omega d}{2v_0} \right)$$

$$= V_1 \frac{\sin \theta_g / 2}{\theta_g / 2} \sin\left(\omega t_0 + \frac{\theta_g}{2} \right)$$

β_i = beam coupling coefficient of input (buncher) cavity by definition

$$\beta_i = \frac{\sin \theta_g / 2}{\theta_g / 2} \qquad (5.4)$$

$$V_{avg} = V_1 \beta_i \sin\left(\omega t_0 + \frac{\theta_g}{2} \right)$$

As we have seen earlier $v_0 = \sqrt{\frac{2eV_0}{m}}$

|||ly $u(t_1) = \sqrt{\frac{2e}{m}} \cdot \sqrt{V_1 \beta_i \sin\left(\omega t_0 + \frac{\theta_g}{2} \right) + V_0}$

$$= \sqrt{\frac{2e}{m} V_0 \left[1 + \frac{\beta_i V_1}{V_0} \sin\left(\omega t_0 + \frac{\theta_g}{2} \right) \right]}$$

Bunching Process of Electrons

All the electrons in the beam will drift with a uniform velocity of " v_0 "at t =t_0 i.e. at time of entry into the buncher cavity. For $t_2 > t > t_0$ i.e. in the cavity gap the velocity of electrons vary with time depending upon the instantaneous field V_1sinwt

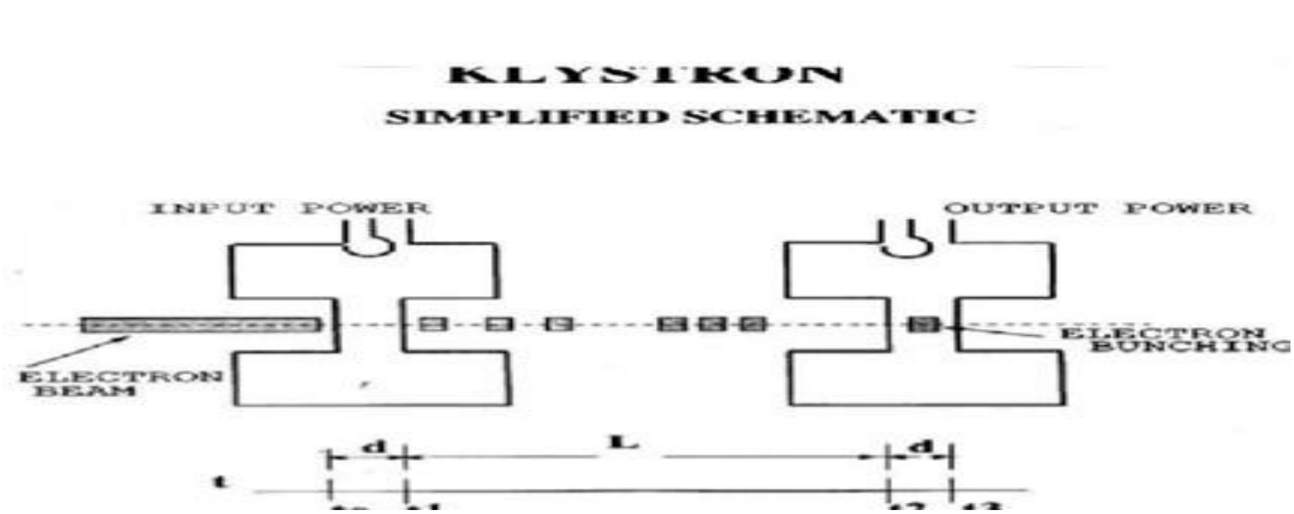
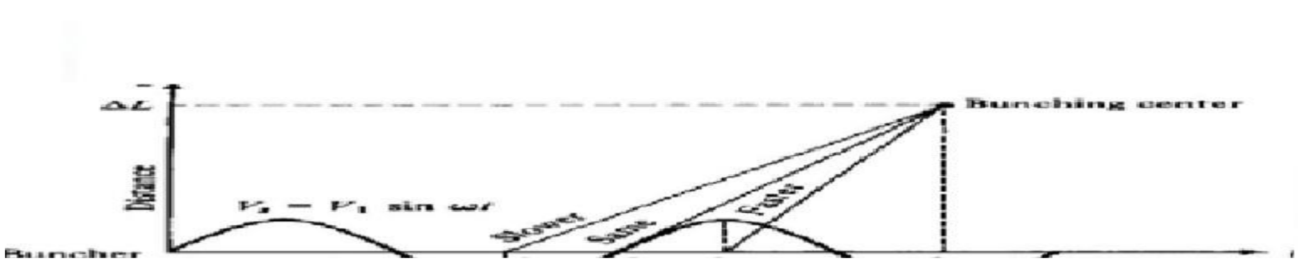


Fig 5.2: Bunching process in 2-cavity klystron

Consider three arbitrary electrons a, b and c passing thro the gap when the field is –ve max, zero and +ve max respectively at time instances t_a, t_b and t_c.



Apple gate diagram

Velocity of electron „b" = $v_b = v_0$ (field zero)

Velocity of electron „a" = $v_a < v_0 = v_{\min}$ (-ve field)

Velocity of electron „c" = $v_c > v_0 = v_0 = v_{\max}$ (+ve field)

Let us consider that these three electrons draft with different velocities and meet (bunch) together at $t = t_d$ at a length ΔL from buncher cavity.

$$\Delta L = v_{\min} (t_d - t_a) \quad (5.7)$$

$$\Delta L = v_0 (t_d - t_b) \quad (5.8)$$

$$\Delta L = v_{\max} (t_d - t_c) \quad (5.9)$$

$$t_c - t_b = t_b - t_a = \pi / 2w \text{ (1/4 of time period)} \quad (5.10)$$

$$\Delta L = v_{\min} (t_d - t_a) = v_{\min} (t_d - t_b + \pi/2\omega) \quad (5.7A)$$

$$\Delta L = v_{\max} (t_d - t_c) = v_{\max} (t_d - t_b - \pi/2\omega) \quad (5.8A)$$

$$v_{\min} = v(t_1) = v_0\left(1 - \frac{\beta_i V_1}{2V_0}\right) \qquad (5.12)$$

Substituting equation 12, 11 in equation 7A and 8A

$$\Delta L = v_0(t_d - t_b) + \left[v_0 \frac{\pi}{2\omega} - \frac{v_0 \beta_i V_1}{2V_0}(t_d - t_b) + \frac{v_0 \beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \qquad (5.13)$$

$$\Delta L = v_0(t_d - t_b) + \left[-v_0 \frac{\pi}{2\omega} + \frac{v_0 \beta_i V_1}{2V_0}(t_d - t_b) + \frac{v_0 \beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \qquad (5.14)$$

Subtracting Eqn 5.14 from Eqn 5.13

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

$$\frac{v_0 \beta_i V_1}{2V_0}(t_d - t_b) = v_0 \frac{\pi}{2\omega} 1 + v_0 \frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}$$

$$\frac{v_0 \beta_i V_1}{2V_0}(t_d - t_b) = v_0 \frac{\pi}{2\omega}\left[1 + \frac{\beta_i V_1}{2V_0}\right] \approx \frac{v_0 \pi}{2\omega}$$

$$\text{since} \quad \frac{\beta_i V_1}{2V_0} << 1$$

$$t_d - t_b = \frac{\pi V_0}{w \beta_i V_1} \qquad (5.15)$$

From Equation 5.8 and 5.15

$$\Delta L = v_0 \frac{\pi V_0}{w \beta_i V_1} \qquad (5.16)$$

ΔL is theoretical value of distance from buncher cavity at which bunching of electrons takes place. Refer Fig -5.1

Equation 5.16 gives the design parameter for spacing between buncher and catcher cavities.

However equation – 5.16 is only an approximation, because mutual repulsive force between the electrons in the highly densed beam are not taken into consideration. It will be seen later that optimum spacing between the two cavities “L” optimum is given by (for maximum degree of bunching)

$$L_{optimum} = \frac{3.682 v_0 V_0}{\omega \beta_i V_1}$$

Which is closer to equation - 5.16

(For derivation refer equation - 5.28)

Let T= Transit time for on electron travel distance „L" (function of „t")

L = spacing between two cavities

Let T_0 = Transit time for electron when the field in buncher cavity is i.e. $v(t_1) = v_0$

$$T_0 = \frac{L}{v_0} \qquad (5.18)$$

$$T = \frac{L}{v(t_1)}$$

Substituting for $v(t_1)$ from equation 5

$$T = \frac{L}{v_0\left[1+\frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right]}$$

$$T = \frac{L}{v_0}\left[1+\frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right]^{-1}$$

Using binomial expansion $(1+x)^{-1}= 1-x$ for $x<<1$ and $V_1<<V_0$, $T_0 = L/v_0$

$$T = T_0\left[1-\frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \qquad (5.19)$$

Multiplying above equation by 'ω'

$$\omega T = \omega T_0\left[1-\frac{\beta_i V_1}{V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \qquad (5.20)$$

Let θ_0 = Angular variation in the signal during time 'T_0'

$$\omega T = \omega T_0 - \frac{\omega T_0 \beta_i V_1}{V_0} \sin\left(\omega t_1 - \frac{\theta_g}{2}\right)$$

$$\omega T = \theta_0 - X \sin \omega t_1 - \frac{\theta_g}{2}$$

$$where\ X = \frac{\beta_i V_1}{2V_0} \theta_0$$

X is called Bunching parameter of Klystron

The second design criterion is that the maximum energy will be transferred by the electrons to the catcher cavity when the bunch enters the cavity while the field is at negative peak. Assuming the buncher and catcher cavities are at same phase the above condition can be expressed mathematically

$\theta_0 = \omega T_0 = 2\pi n - \pi/2 = 2\pi N$ (5.21A)

Where n is an integer and N is number cycles the angle has undergone chages during the transit time T_0

Expression for output current

Let us try to establish the relation between I_0 = dc current passing through buncher vacity and „i_2" ac current in the catcher cavity.

Making use of law of conservation

Let charge „dQ_0" pass through the buncher gap at a time interval „dt_0" and we will assume the same amount of charge passes through the catcher gap later in time interval „dt_2"

$dQ_0 = I_0\, dt_0$

$dQ_0 = |I_0\, dt_0| = |i_2\, dt_2|$ (5.22)

We have earlier defined t_0, t_1, t_2 such that

$$\tau = t_1 - t_0$$

$$t_1 = t_0 + \tau$$

$T = t_2 - t_1$, $\quad T = t_2 - (t_0 + \tau)$

From equation 19

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

$$t_2 = t_0 + \tau + T_0\left[1 - \frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right]$$

Multiplying by „ω"

$$\omega t_2 = \omega t_0 + \omega\tau + \omega T_0\left[1 - \frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right]$$

$$\omega t_2 = \omega t_0 + \theta_g + \theta_0 - \frac{\theta_0 \beta_i V_1}{2V_0}\sin\left(\omega t_0 + \frac{\theta_g}{2}\right)$$

we have $X = \dfrac{\theta_0 \beta_i V_1}{V_0}$

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

Differentially above equation w.r.t. „t_0"

θ_g, θ_0 are constants w.r.t. „t"

$\frac{dt_2}{dt_0}$ ● X ... g and

cos ... t_0 . 2

g

$$dt_2 \bullet dt_0 \triangle 1 \; X \cos \; t_0 \,. \quad 2 \qquad (5.23)$$

From equation 22 and 23

$$I_0 |dt_0| = |i_2\, dt_2| = i_2\, dt_0 \left[1 - X\cos\left(\omega t_0 - \frac{\theta_g}{2}\right)\right]$$

$$i_2(t_0) = \frac{I_0}{1 - X\cos\left(\omega t - \theta_0 - \frac{\theta_g}{2}\right)} \qquad (5.24)$$

i_2, the beam current at catcher cavity is a periodic waveform of period $\frac{2\pi}{\omega} = \frac{1}{f}$, about dc current I_0

$$i_2 = I_0 + \sum_{n=1}^{\infty} 2I_0 \beta_0 J_n(nX)\cos n\omega(t_2 - \tau - T_0) \qquad (5.25)$$

Where n = integer

Derivations of above equation is out of preview of the syllabus

$J_n(x)$ = n^{th} order bessel function of 1^{st} kind

We are interested in the fundamental component i.e. n=1, ac beam current

Neglecting dc current and higher order of ac current i.e. n>2

I_f = fundamental component of ac current from equation 25 in catcher cavity whose beam complex coefficient = β_0

$$I_f = 2I_0 J_1(X)\beta_0 \cos w(t_2 - \tau - T_0) \qquad (5.26)$$

Let I_{fmax}= magnitude of I_f in catcher cavity

$$I_2 = 2\beta_0 I_0 J_1(X) \qquad (5.27)$$

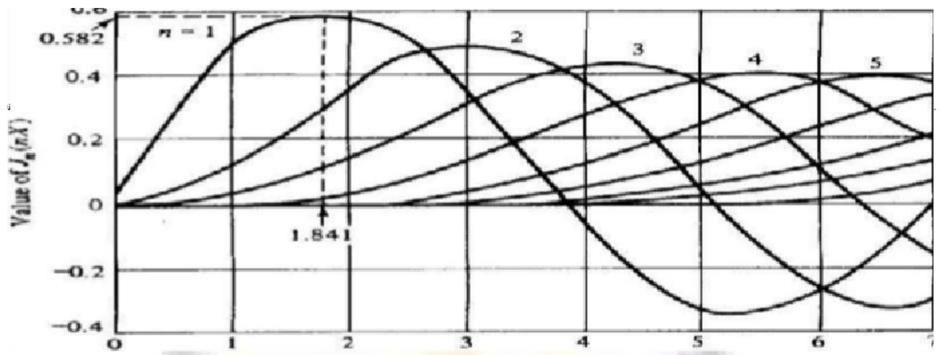


Fig 5.4: Bessel function J_n (nX)

J_1(X) is maximum at X = 1.841 i.e. $J_1(1.841) = 0.582$ from Bessel function

Where X = Bunching parameter of Klystron as defined in equation 21

$$X = \frac{\beta_i V_1}{2V_0}\theta_0 = \frac{\beta_i V_1}{2V_0}\frac{\omega L}{v_0}$$

The same equation is given theoretically as equation

The Output power and beam loading

Let I_2 is max value of current in the catcher cavity with $\beta=\beta_0$

From equation 5.27

$$I_2 = 2\beta_0 I_0 J_1(X) \qquad (5.29)$$

Power Output and efficiency of Klystron

The equivalent output circuit of Klystron is

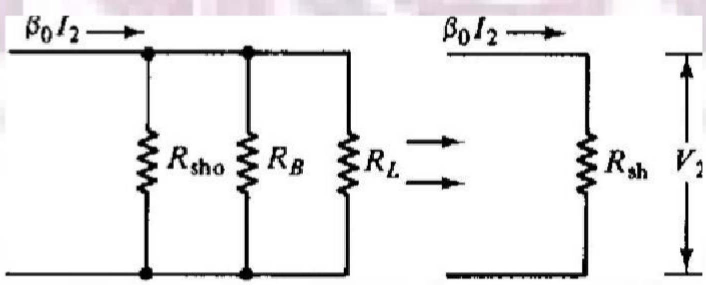


Fig 5.5 : Output equivalent circuit

Where R_{sho} = Wall resistance of catcher cavity

R_B = beam loading resistance

R_L = External load resistance

R_{sh} = Effective shunt resistance = R_{sho} || R_B || R_L

$$i_{rms} = \frac{i_{f\max}}{\sqrt{2}} = \frac{I_2}{\sqrt{2}} = \frac{2I_0\beta_0 J_1(X)}{\sqrt{2}}$$

$$P_{output} = i_{rms}^2 R_{sh} = 2I_0^2\beta_0^2 J_1^2(X) R_{sh} = \beta_0 I_0 J_1(X) V_2 \qquad (5.29A)$$

$$\max imum\ output\ voltage = V_2 = i_{f\,rms} R_{sh} = 2\beta_0 I_0 J_1(X) R_{sh} \qquad (5.30)$$

$$Efficiency = \eta = \frac{P_1}{P_{dc}} = \frac{2I_0^2\beta_0^2 J_1^2(X) R_{sh}}{V_0 I_0}$$

$$\eta = \frac{\beta_0 I_0 J_1(X) V_2}{V_0 I_0} = \frac{\beta_0 J_1(X) V_2}{V_0} \qquad (5.31)$$

Maximum theoretical efficiency of Klystron is

β_0 =1, $J_1(X)$=0.582, $V_2=V_0$

η_{max} = 58.2 % theoretical

Practically η ≈ 40%

Condition for maximum transfer of energy to catcher cavity

From equation 5.21A we have $\theta_0 = \omega T_0 = 2\pi n - \pi/2 = 2\pi N$ and from equation 5.21

$$X = \frac{\beta_i V_1}{2V_0}\theta_0 = \frac{\beta_i V_1}{2V_0} 2\pi N$$

REFLEX KLYSTRON

Reflex klystron is a single cavity law power microwave oscillator. The characteristics of Reflex Klystron are

Power output: 10- 500mw

Frequency range: 1 to 25 GHz

Efficiency: 10-20%

Applications

1. Widely used in the as a source for microwave experiments
2. Local oscillator in microwave receivers

The theory of the 2-cavity klystron can be applied to the analysis of Reflex klystron with slight modifications

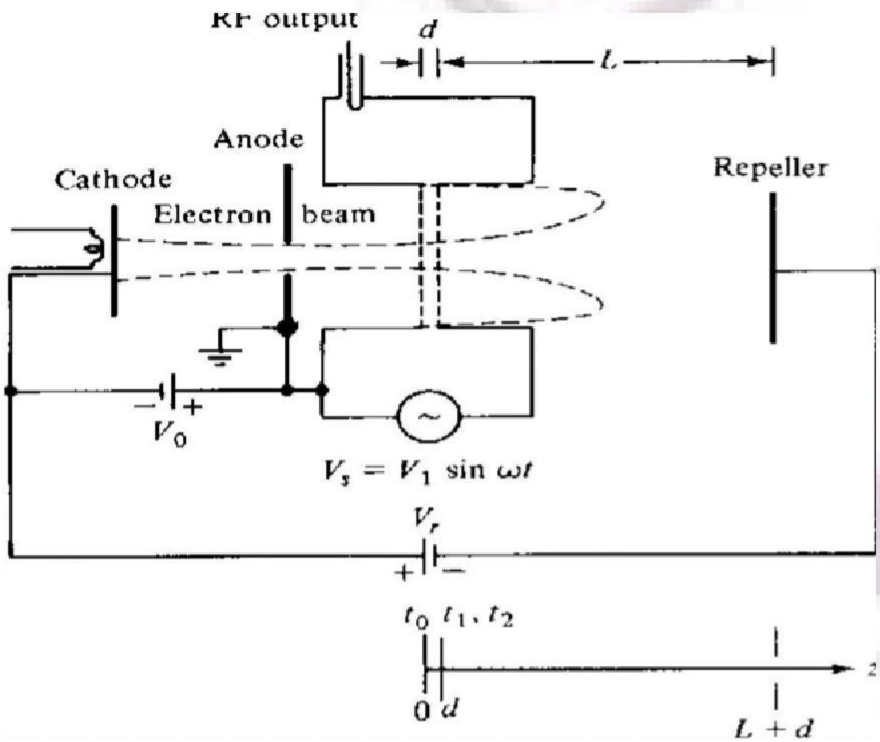


Fig 5.6: Schematic digram of Reflex Klystron

The components of Reflex Klystron are

1. Cathode
2. Anode grid
3. Cavity resonator at potential of $+v_0$ w.r.t cathode
4. Repeller at potential of $-V_r$ w.r.t. cathode

Formation of electron beam with uniform velocity v_0 up to civility resonator is similar to that of 2-cavity klystron

$$v_0 = 0.593 \times 10^6 \sqrt{V_0} \; m/s$$

Due to dc voltage in the cavity circuit, RF noise is generated in the cavity. This em noise field in the cavity get pronounced at cavity resonant frequency and acts as a small signal microwave voltage source of V_1 sin wt.

The electron beam with uniform velocity v_0 when enters the cavity undergoes velocity modulation as in the case of 2-cavity klystron.

Let t_0 = time at which electron enters the cavity gap

t_1 = time at which electron leave the cavity gap

d = cavity gap

Z = Axis as shown in schematic diagram

Z = 0 at the input gap of cavity

Z = d at the output gap of cavity

Z = L at the reseller

From equation 5 of 2 cavity klystron

Some electrons are accelerated by the accelerating field (during +ve cycle of RF field) and enter the repeller space with greater velocity compared to the electrons with unchanged velocity, some electrons are decelerated by the decelerating field (during –ve cycle of RF field) and enter repeller space with less velocity

All the electrons entering repeller space are retarded by the repeller which is at a -ve potential of $-v_r$. All the electrons are turned back and again enter the cavity in a bunched manner. The bunch re enter the cavity and when field in the cavity is a retarding field bunches convey kinetic energy to the cavity. The cavity converts this kinetic energy into electron magnetic energy at the resonant frequency resulting in the sustained oscillations and therefore the output of the cavity is V_1 sin ωt

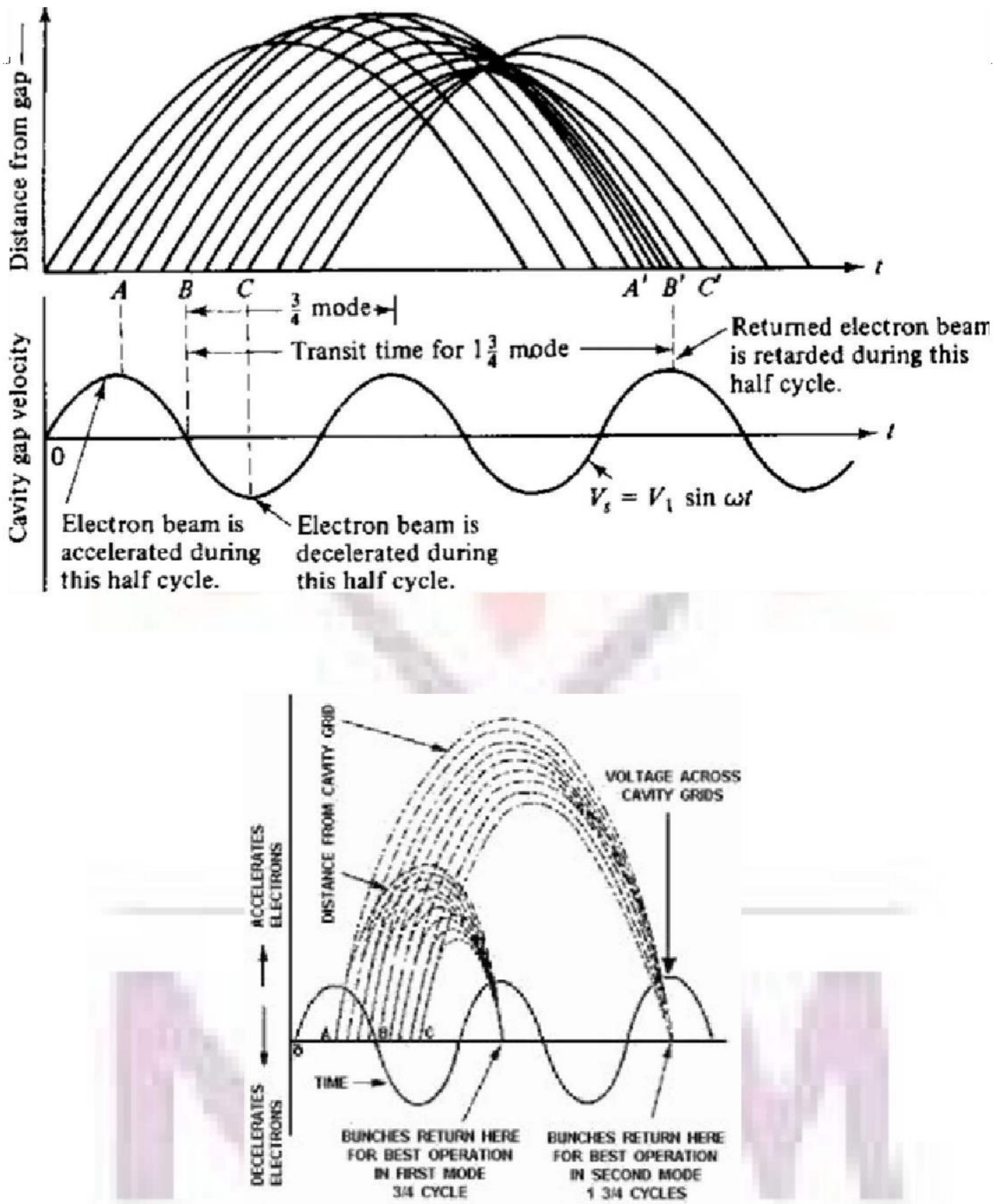


Fig 5.7: Applegate diagram of Reflex Klystron

Let „b" be the reference electron at t = t_2 for our analysis. Electron „b" is passing through the cavity gap while the field is zero (-ve shape) when the electrons a,b,c… leave the cavity i.e. at z = d, the velocity is given by equation

- These electrons are subjected to retarding field due to repeller voltage during the drift space from z = d to z = L. the retarding field in the drift space is given by

$$E \bullet \frac{V_r . V_0 . V_1 \sin wt}{L} \quad (5.47)$$

The force equation for an electron in the repeller region is given by

$$m\frac{d^2 z}{dt^2} \bullet eE \bullet e\frac{V_r . V_0 . V_1 \sin wt}{L}$$

Since $V_1 << V_0$, $V_1 << V_r$

$$m\frac{d^2 z}{dt^2} = -eE = -e\frac{[V_r + V_0 + V_1 \sin wt]}{L}$$

Since $V_1 << V_0$, $V_1 << V_r$

$$m\frac{d^2 z}{dt^2} = -e\frac{(V_r + V_0)}{L} \quad (5.48)$$

Integrating the above equation

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

Where

K_1 = integration constant

t_0 = Time at the electron enters the gap

t_1 = Time at the electron leave the gap

t_2 = Time at the electron re-enters the gap due to retarding field at $t = t_1$, $z = d$, $v(t_1) = dz / dt$

$K_1 = dz/ dt = v(t_1)$

Integrating the above equation once again

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

At $t= t_1$, $z= d$

$K_2 = d$

$$z = -e\frac{(V_0 + V_r)}{2mL}(t - t_1)^2 + v(t_1)(t - t_1) + d \qquad (5.49)$$

At $t = t_2$ electrons returns of cavity after retardation at $t = t_2$, $z=d$ substituting this in above equation.

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

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

Let T be rannd trip transit time = t_2-t_1

$$O = (t_2 - t_1)\left[\frac{-e(V_0 + V_r)}{2mL}(t_2 - t_1)^2 + v(t_1)\right]$$

At $t = t_2$ electrons returns of cavity after retardation at $t = t_2$, $z=d$ substituting this in above equation.

T_O"Is the round trip transit time of electron „b" which is learning the cavity at velocity $v(t_1) = v_0$

T"$_0$ is a function of V_r

$\omega(t_2-t_1) = \omega T$

$$\theta' = \omega T' = \omega T'_0 - \frac{\beta_i V_i}{2V_0} \sin(\omega t_1)$$

Where X" is bunching parameter of Reflex Klystron

Power output and efficiency of Reflex Klystron

In case of 2-cavity klystron, we had seen that the maximum transfer of kinetic energy to the cavity takes place when the electron bunch enters when the field is -ve peak

Similarly in the case of reflex Klystron, the bunch must enter cavity when the field is +ve peak. (This is because the direction of electron bunch entering into the cavity is 180^0 opposite to that of 2-cavity Klystron) round trip transit time of reference electron is

$$\omega(t_2 - t_1) = \omega T_0 = \left(n - \frac{1}{4}\right)2\pi = 2\pi n - \frac{\pi}{2} = 2\pi N \qquad (5.53)$$

When n = 1,2,3……………….

Let N= n-1/4 is called the mode number

Therefore $\theta_0 = 2\pi N$

Applying the same analogy of 2-cavity klystron and using equation 25, the current in the cavity can be expressed as

$$i_2 = -I_0 - \sum_{n=1}^{\infty} 2I_0 J'_n(n\times')\cos[\pi(\omega t_2 - \theta_0 - \theta_g)] \qquad (5.54)$$

The fundamental component of current in the cavity if at n =1 is

$$i_f = -\beta_i i_2\big|_{n=1} = 2I_0\beta_i J_1(\times^1)\cos(\omega t_2 - \theta_0) \qquad (5.55)$$

$$\theta_g << \theta_0$$

Maximum magnitude of fundamental component current in the cavity I_2

$$I_2 == 2I_0\beta_i J_1(\times^1)$$

V_2 = output voltage of the cavity = V_1 (except for the phase difference)

$$V_1 = V_2 = 2I_0\beta_i J_1(\times^1)R_{sh} \qquad (5.57)$$

$$output\ \ power = P_{ac} = i^2_{rms}.R_{sh} = \left(\frac{2I_0\beta_i J_1(X^1)}{\sqrt{2}}\right)^2 R_{sh} \qquad (5.58)$$

$$P_{ac} = 2I^2{}_0\beta^2{}_i J_1{}^2(X^1)R_{sh} \qquad (5.59)$$

$$P_{ac} = V_1.I_0\beta_i J_1(X^1) \qquad (5.60)$$

We have earlier seen that

$$X^1 = \frac{\beta_i V_1}{2V_0}\theta_0 = \frac{\beta_i V_1}{2V_0}\left(2\pi n - \frac{\pi}{2}\right)$$

$$\frac{V_1}{V_0} = \frac{2X^1}{\beta_i\left(2\pi n - \frac{\pi}{2}\right)} \qquad (5.61)$$

$$\frac{P_{ac}}{P_{dc}} = Power\ \ Efficiency\ = \ \eta = \frac{V_1 I_0 \beta_i J_1(X^1)}{V_0 I_0} \qquad (5.62)$$

$$= \frac{V_1}{V_0}.\frac{\beta_i J_1(X^1)}{I_0} = \frac{2X^1 J_1(X^1)}{\left(2\pi n - \frac{\pi}{2}\right)}$$

$$\eta = \frac{2X^1 J_1(x^1)}{\left(2\pi n - \frac{\pi}{2}\right)} \qquad (5.63)$$

The product $X_1 J_1(X^1)$ is maximum at $X^1 = 2.408$, $J_1(X^1) = 0.52$

$X^1 J_1(X^1)_{max} = 1.25$ at $X^1 = 2.408$

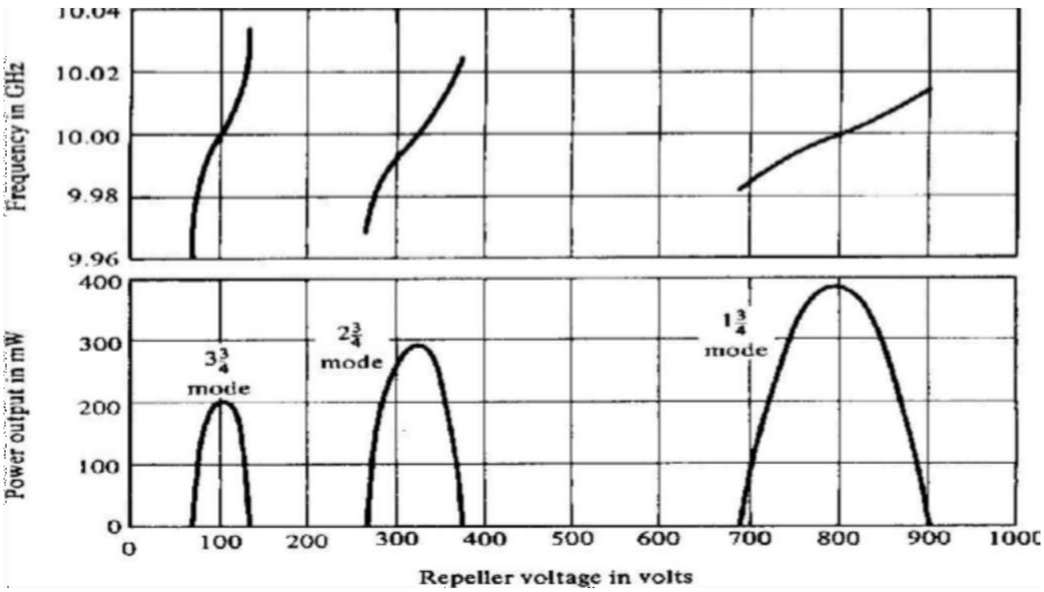
$$\eta_{max} = \frac{2 \times 1.25}{\left(2\pi n - \frac{\pi}{2}\right)}$$

At n = 2 (n=1 too short a value)

$$\eta_{max} = 0.227 \text{ or } 22.7 \qquad (5.64)$$

From equation 5. 50 we have

$$T'_0 = \frac{2mLv_0}{e(V_0 + V_r)} \text{ where } v_0 = \sqrt{\frac{2e}{m}V_0}$$



From equation 5.53, $\omega T'_0 = 2\pi n - \pi/2$

$$\omega T_0 = \frac{2\omega m L v_0}{e(V_0+V_r)} = \frac{2\omega m L}{e}\cdot\sqrt{\frac{2e}{m}}\frac{\sqrt{V_0}}{V_0+V_r} = 2\pi n - \frac{\pi}{2} \quad (5.65)$$

$$\frac{V_0}{(V_0+V_r)^2} = \frac{\left(2\pi n - \frac{\pi}{2}\right)^2}{8\omega^2 L^2}\cdot\frac{e}{m} \quad (5.66)$$

The above equation gives relationship between V_0, V_r and 'n' for given V_0, n= f(V_r)

From equation 5. 60 we have $V_1 = \dfrac{2X^1 V_0}{\beta_i\left(2\pi n - \frac{\pi}{2}\right)}$

From equation 5.58, Pac = $V_1 I_0 \beta_i J_1(X^1)$

$$P_{ac} = \frac{2X^1 V_0 I_0 \beta_i J_1(x^1)}{\beta_i\left(2\pi n - \frac{\pi}{2}\right)} = \frac{2V_0 I_0 X^1 J_1(x^1)}{2\pi n - \frac{\pi}{2}} \quad (5.67)$$

Substituting for $2\pi n - \pi/2$ from equation 5.65

$$= \frac{2V_0 I_0 X^1 J_1(x^1)}{2\omega m L}\sqrt{\frac{m}{2e}}\cdot\frac{e(V_0+V_r)}{\sqrt{V_0}}$$

Equation 5.68 gives relationship between relationship between

1. V_r and P_{ac}
2. ω and P_{ac}

Helix Travelling Wave Tubes

In the previous topics klystrons and reflex klystrons were analysed in some detail.When it comes to study of TWTs it is appropriate to compare the basic operating principles of both TWT and the klystron. In the case of TWT, the microwave circuit is non-resonant 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 klystrons.

1. 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.
2. The wave in the TWT is a propagating wave ;the wave in the klystron is not.
3. In the couple cavity TWT there is a coupling effect between the cavities, whereas each cavity in the klystron operates independently.

A**traveling-wavetube(TWT)**isaMicrowaveAmplifierwithfollowingcharacteristics:

1. Low Power Amplifier :up to10 kW
2. Frequency Range:3GHz–50GHz
3. Wide Bandwidth: about800MHz
4. Powergain:upto60dB
5. Efficiency:20–40%

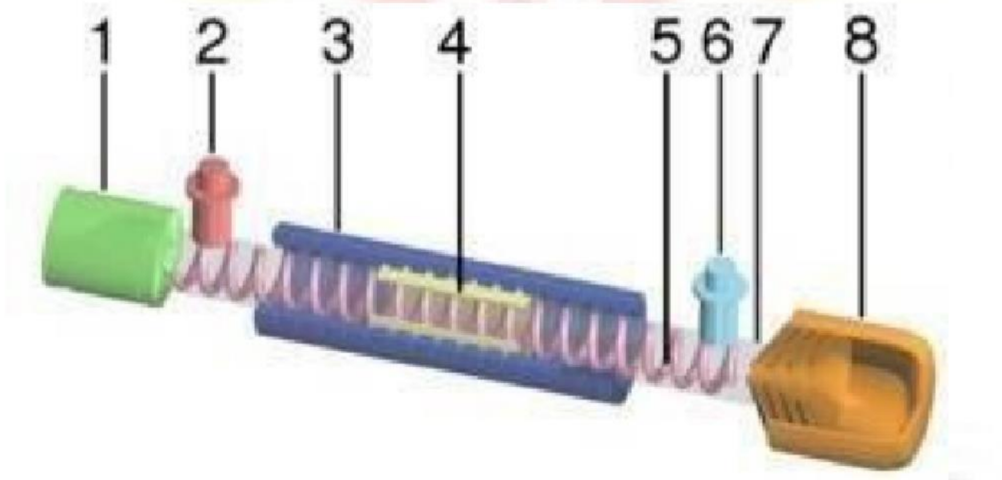
ComparisonbetweenTWTandKlystronAmplifier

S.No.	KlystronAmplifier	TWT Amplifier
1	Linear beam „O"Type	Linear beam „O"Type
2	Uses input and output resonant cavities	Usesnon-resonantwavecircuit
3	Narrowbandamplifier	WidebandamplifierBW800MHz

4	Interactionbetweenelectrons and the field is very short	Longer interaction
5	Nonpropagatingwave	Propagatingwave

The TWT operates on the principle of slow wave. It is a not resonant „O"-Type microwave device. Its operation is base on the interaction between the waves in the travelling wave structure and the electronic beam. The main elements of the TWT Amplifier are:

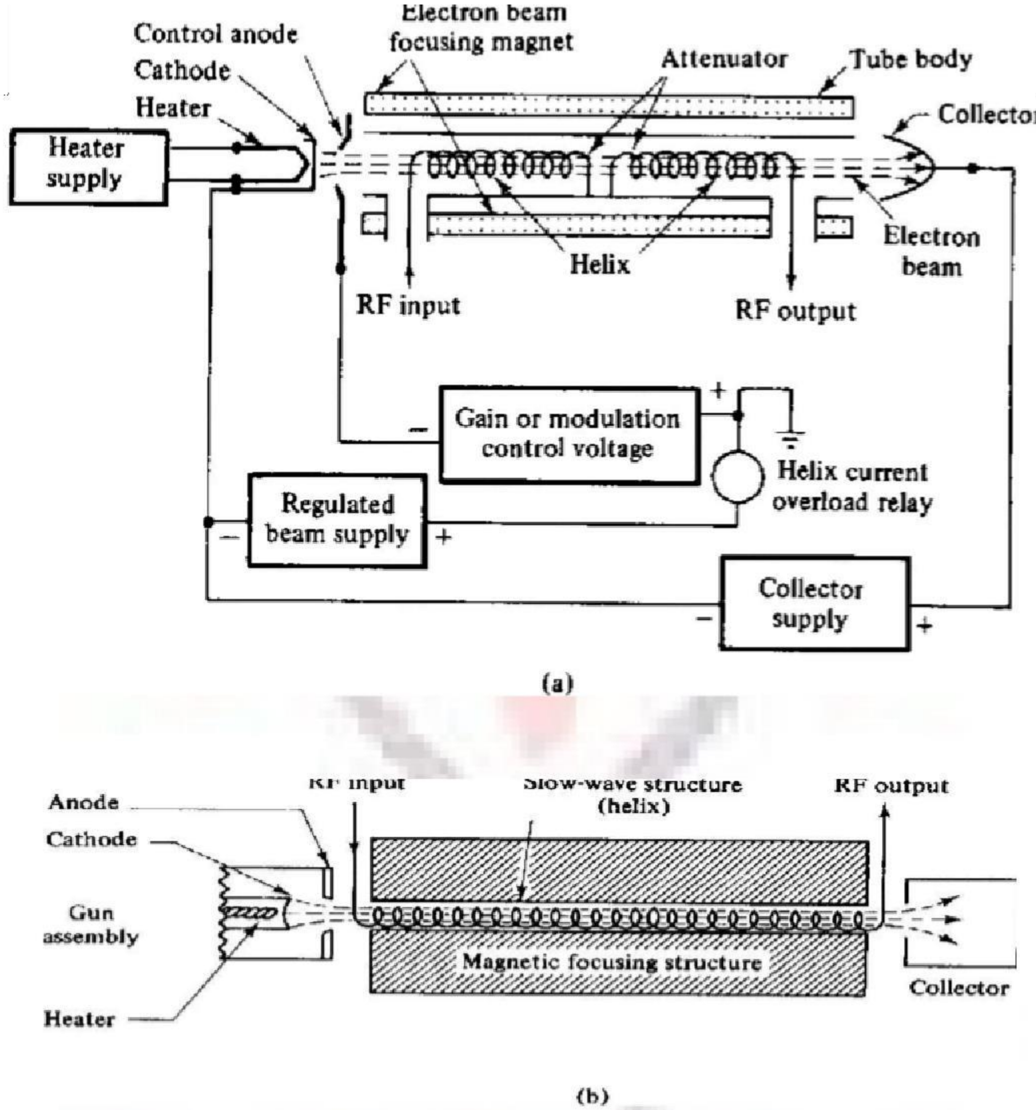
(1) Electrongun;
(2) RFinput
(3) Magnets
(4) Attenuator
(5) Helixcoil
(6) RF output
(7) Vacuumtube
(8) Collector



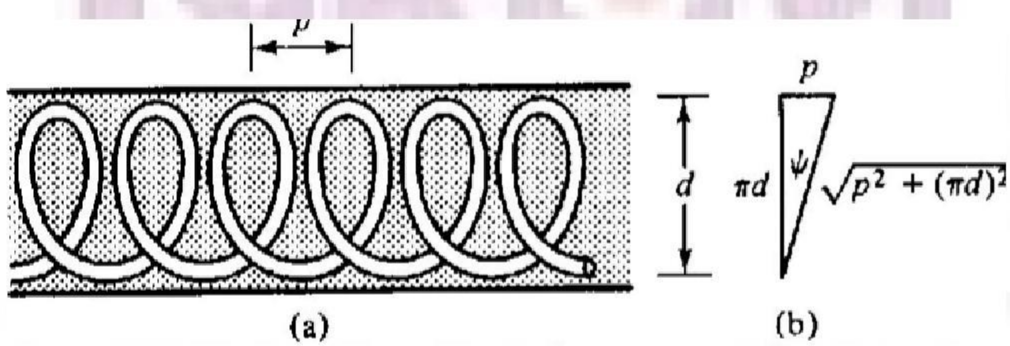
TWT.

Description

The device is an elongated vacuum tube with an electron gun (a heated cathode that emits electrons) at one end. A magnetic containment field around the tube focuses the electrons into a beam, which then passes down the middle of a wirehelix that stretches from the RF input to the RF output, the electron beam finally striking a collector at the other end. The applied RF signal propagates around the turns of the helix and produces and electric field at the center of the helix, with direction of propagation along helix axis.



HelixTravelingWaveTube(a)Schematic Diagram(b)SimplifiedCircuit



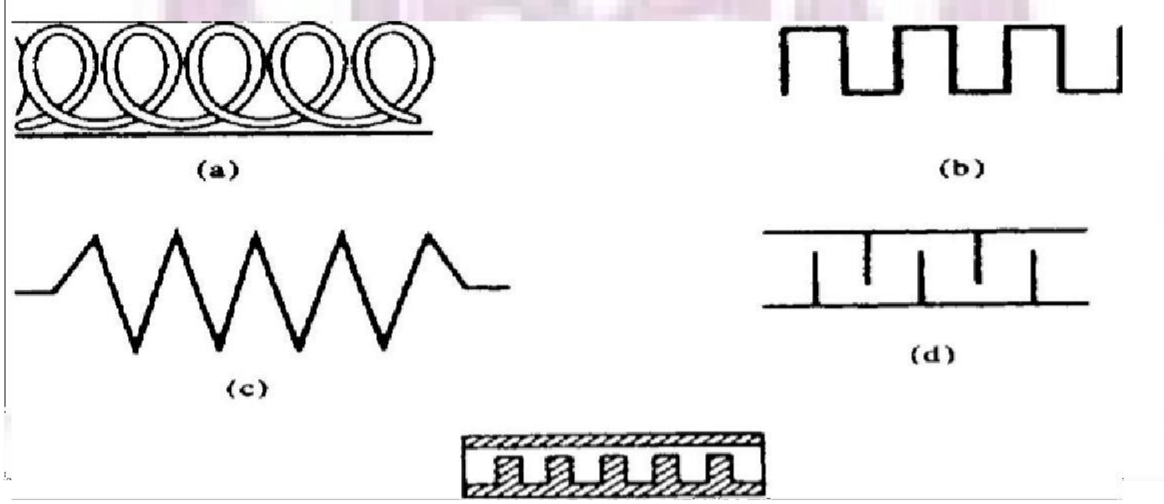
HelicalSlowWaveStructure (a)HelicalCoil(b)One turnofhelix

This is termed as O-type traveling wave tube. The slow-wave structure is either the helical type or folded back type. The applied signal propagates around the turns ofthe helix and produces an electric field at the center of the helix, directed along the helix axis. The helix acts as a delay line, in which the RF signal travels at near the same speed along the tube as the electron beam. The axial electric field progresses with a velocity that is very close to the velocity of light multiplied by the ratio of helix pitch to helix circumference.When electrons enter the helix tube, an interaction takes place between themoving axial field and the moving electrons. On the average, the electrons transfer energy to the wave on the helix. This interaction causes the signal wave on the helix to become larger.The electronsentering the helix at zero fields are not affected by the signal wave; those electrons entering the helix at the accelerating field are accelerated, and those at the retarding field are decelerated. As theelectrons travel further along the helix, they bunch at the collector end. The bunching shifts the phase by$\pi/2$. Each electron in thebunch encounters a stronger retarding field. Then the microwave energy of the electrons is delivered by the electrons bunch to the wave on helix. The amplification of the signal wave is accomplished.

An attenuator placed on the helix, usually between the input and output helices, prevents reflected wave from traveling back to the cathode and there by suppresses the oscillations if any.

Slow wave structures

Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity in a certain directions so that the electron beam and the signalwave can interact. The phase velocity of a wave in ordinary waveguides is greater that 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 the figure given below.



Applications

1. TWTAs are commonly used as amplifiers in satellitetransponders, where theinput signal is very weak and the output needs to be high power.
2. TWT is used as transmitter amplifier particularly in airborne and shop borne fire-control radar systems, Satellites, and in electronic warfare and self-protection systems. In these types of applications, a control grid is typically introduced between the TWT's electron gun and slow-wave structure to allow pulsed operation. The circuit that drives the control grid is usually referred to as a grid modulator.

Another major use of TWTAs is for theelectromagnetic compatibility (EMC) testingindustry for immunity testing of electronic devices.