UNIT 1

MICROWAVE TUBES AND HELIX TWTs

Syllabus

MICROWAVE TUBES: Limitations and Losses of conventional Tubes at Microwave Frequencies, Microwave Tubes – O Type and M Type Classifications, O-type Tubes: 2 Cavity Klystrons – Structure, Reentrant Cavities, Velocity Modulation Process and Applegate Diagram, Bunching Process and Small Signal Theory – Expressions for O/P Power and Efficiency. Reflex Klystrons – Structure, Velocity Modulation and Applegate Diagram, Mathematical Theory of Bunching, Power Output, Efficiency, Oscillating Modes and O/P Characteristics.

HELIX TWT: Types and Characteristics of Slow Wave Structures; Structure of TWT and Amplification Process (qualitative treatment), Suppression of Oscillations, Gain Considerations.

LEARNING OBJECTIVES

- Limitations and losses of conventional tubes at microwave frequencies.
- Microwave tubes and their classification as O-type and M-type.
- Structure, working of two cavity klystron O-type tube and derivation of its O/P power and efficiency expressions.
- Structure, working of reflex klystron O-type tube and derivation of its O/P power and efficiency expressions. Along with this oscillating modes and O/P characteristics of reflex klystron.
- Types and characteristics of slow wave structures used in travelling wave tubes.
- Structure, amplification process (qualitative treatment), suppression of oscillations and gain considerations of helix TWT

INTRODUCTION

Conventional vacuum tubes, such as triodes, tetrodes and pentodes are still used as signal sources of low output power at low microwave frequencies. However, these tubes are less preferred at microwave frequencies due to their limitations and losses.

In this unit, we study about limitations and losses of conventional vacuum tubes at microwave frequencies. In order to overcome these limitations and losses, O-type and M-type tubes were introduced. We then discuss about klystron amplifier, in fact we discuss the specialized tubes which were developed for microwave frequency application, and klystron is one such tube. Then, we will see reflex klystron as an oscillator, for oscillation we require feedback to be provided and we will see how reflex klystron provides the required feedback, we will see that these devices like klystron or reflex klystron they operate on the principle of velocity modulation. And finally, we will discuss traveling wave tubes or TWTs specially helix type.

PART-A SHORT QUESTIONS WITH SOLUTIONS

Q1. What are the limitations of conventional tubes at microwave frequencies?

(Model Paper, Q1(a) | Dec.-19, (R16), Q1(a))

(or)

What are the limitations of conventional vacuum tubes at microwave frequencies? Nov./Dec.-16, (R13), Q1(a)

Ans:

Conventional tubes cannot be used at microwave frequencies i.e., > 100 MHz due to the following effects.

1. Inter electrode capacitance effect
2. Lead inductance effect
3. Transit time effect
4. Gain-bandwidth limitation
5. Effect due to RF losses
6. Radiation losses.

Q2. Explain the transit time effect in conventional tubes.

April/May-18, (R13), Q1(f)

Ans:

At low frequencies, transit time is negligible compared to the time period of the RF signal applied. Therefore, the plate current, i_p can instantaneously respond to the respective changes in grid voltage, V_g i.e., both i_p and V_g are in phase.

At high frequencies, i_p lags V_g and transconductance, g_m becomes a complex quantity (as the transit time is comparable with the period of the signal). Thus, the gain of the tube amplifier becomes complex even for resistive load, which results in reduced real gain values.

Q3. How microwave tubes are classified?

May/June-19, (R15), Q1(f)

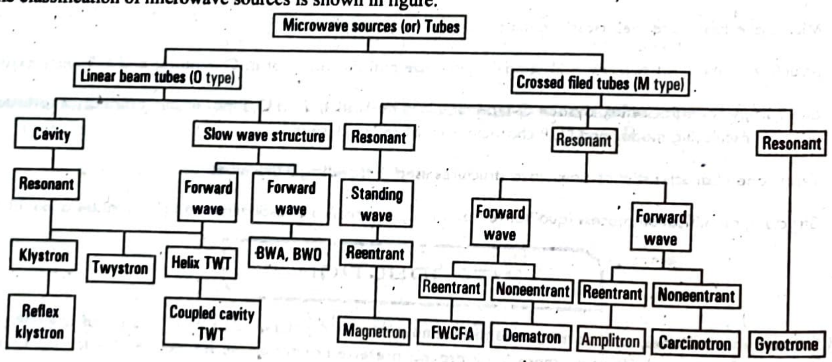
(or)

Classify microwave tubes.

Nov./Dec.-17, (R13), Q1(e)

Ans:

The classification of microwave sources is shown in figure.



Figure

Q4. What are the reentrant cavities?

Ans:

May/June-19, (R15), Q1(e)

A cavity with the metallic boundaries penetrating into its interior is known as "Reentrant Cavity". The devices can provide a very sensitive high-Q microwave mode. The design of reentrant cavities can be highly advantage for electromechanical devices and quantum measurements.

Q5. Define velocity modulation.

Ans:

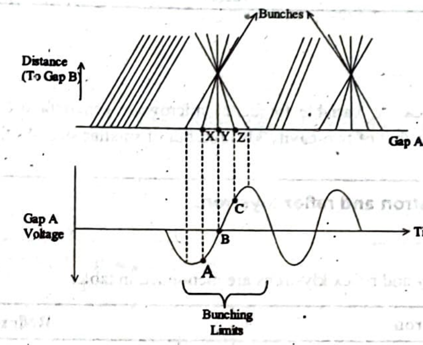
The variation of electron velocity in the drift space region is known as velocity modulation. This technique is mainly employed at microwave or high frequencies only. Thus, this principle is used in klystrons and magnetrons to avoid effects at microwave frequencies.

Q6. Draw typical Applegate diagram.

Ans:

April/May-18, (R13), Q1(e)

The typical applegate diagram is as shown in figure.

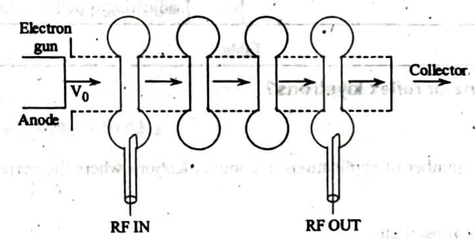


Figure

Q7. Why do practical klystron amplifiers generally have more than two cavities? How can broadband operation be achieved in multicavity klystron?

Ans:

In a multicavity klystron, multiple number of cavities are used as shown in figure.



Figure

The two-cavity klystron suffers from high gains of about 10 to 20 dB. So, a higher overall gain can be achieved by connecting multiple two cavity tubes in cascade, giving the output of each of the tubes to the input of the succeeding one.

In this, each of the intermediate cavities acts as a buncher with the passing electron beam inducing an enhanced RF voltage than the previous cavity. With four cavity Klystron, the power gains of around 50 dB can be obtained. For narrow-band operation, the cavities are tuned to the same frequency and an improved bandwidth is achieved by stagger tuning the cavities up to 80 MHz. Hence, multicavities are used in klystron amplifier.

Q8. What are the performance characteristics of a klystron amplifier?

Ans:

Nov./Dec.-12, (R09), Q5(c)

The performance characteristics of a two-cavity klystron amplifier are as follows,

	Parameter	Value
1.	Operating frequency	250 MHz- 100 GHz (60 GHz nominal)
2.	Power	10 kW - 500 kW (CW) 30 MW (pulsed)
3.	Power gain	15 dB - 70 dB (60 dB nominal)
4.	Bandwidth	10 - 60 MHz
5.	Noise figure	15 dB - 20 dB (sometimes > 25 dB)
6.	Theoretical efficiency	58% (30 - 40% nominal)

Table

Q9. What is a reflex klystron?

Ans:

The reflex klystron is a single cavity, variable frequency microwave generator oscillator. It has low power and low efficiency. It has electron gun similar to that of two-cavity klystron but of smaller size. As the size is small the beam does not require focusing.

Q10. Differentiate two cavity klystron and reflex klystron.

Ans: Nov./Dec.-17, (R13), Q1(f)

The differences between 2-cavity and reflex klystrons are mentioned in table,

	Two-cavity Klystron		Reflex Klystron
1.	It is a two-cavity (input and output cavities) device.	1.	It is a single-cavity (only input cavity) device.
2.	Catcher cavity is used as output cavity.	2.	Repeller is used as output cavity.
3.	Input and output cavities are used for modulation and demodulation respectively.	3.	Single cavity is used for both modulation and demodulation.
4.	Bunching of electrons is limited.	4.	Maximum bunching of electrons can be obtained by adjusting repeller voltage.

Table

Q11. What are the applications of reflex klystrons?

Ans:

Reflex klystron tube posses number of applications in communications where the variable frequency is required it finds applications in,

1. Microwave receivers as a local oscillator.
2. Compact microwave links.
3. Radar receivers.
4. Parametric amplifiers as a pump oscillator
5. Variable frequency microwave generators as a signal source.

Q12. What is a slow wave structure?

Ans: Nov./Dec.-18, (R13), Q1(e)

Slow-wave structures are the circuits, which provides interaction between electron beam and signal wave by reducing the velocity of wave in particular direction.

Q13. What are the advantages of slowwave structures?

Ans: (Model Paper, Q1(f) | Dec.-19, (R16), Q1(f) M[3])

In TWT, the electron beam cannot accelerate faster than the waves travelling on wire. This is because of the waves travelling at the speed of light and increased in its amplitude along the length of TWT. Due to this drawback, bunching process does not occur.

This drawback can be eliminated by using slow wave structures in TWT. These structures allows the bunching process to occur by reducing the speed of travelling waves below the electron beam speed. This setup also produces large gain over a wide bandwidth.

Q14. What is the need of Helix in TWT?

Ans:

The reasons for using helix in TWT,

1. Helix decreases the velocity of the wave in particular direction to establish the communication between signal and electron beam.
2. It provides the large gain over a wide bandwidth.
3. It offers low impedance.

Q15. Write the advantages of travelling wave tubes.

Ans:

The advantages of TWT are,

1. TWTs have very high gain of about more than 40 dB.
2. Noise figure in TWTs is as low as 6 dB.
3. TWTs have highest BW among amplifiers i.e., 30 to 120%.
4. They have high power rating ranging from few watts to 20,000 W.

Q16. Mention the characteristics and applications of TWT.

Ans:

Characteristics of TWT

1. Frequency of operation : 300 MHz to 50 GHz
2. Efficiency : 20 to 40%
3. Power gain : 40 dB to 60 dB
4. Bandwidth : about 800 MHz
5. Power output : Upto 10 k/Watts.

Applications of TWT

1. Travelling wave tubes are used as low noise RF amplifiers in,
2. These are used as repeater amplifier in wide band communication links and long distance telephony.
3. Travelling wave tubes are used as output power tubes in communication satellites because of its long tube life i.e., 50,000 hrs.
4. Due to larger power and bandwidth, continuous wave high power TWT's are used in troposcatter links.
5. Travelling wave tubes are also used in airborne and shipborne pulsed high power radars and ECM ground based radars.

PART-B ESSAY QUESTIONS WITH SOLUTIONS

1.1 MICROWAVE TUBES

1.1.1 Limitations and Losses of Conventional Tubes at Microwave Frequencies

Q17. In detail explain the limitations of conventional tubes at microwave frequencies.

(Model Paper, Q2(a) | March-21, (R16), Q4(a))

(or)

State the limitations of conventional tubes at high frequencies.

April/May-18, (R13), Q6(b)

(or)

What are the limitations of conventional vacuum tubes to operate at microwave frequencies?

May/June-13, R09, Q5(b)

(or)

What are the limitations of conventional tubes at microwave frequencies?

Nov./Dec.-12, (R09), Q5(a)

Ans:

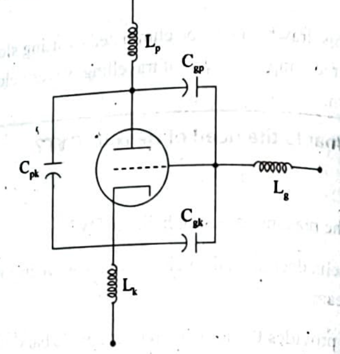
Conventional tubes are the tubes which are useful only for low microwave frequencies. The commonly use conventional tubes are triodes, pentodes and tetrodes.

Due to the following limitations conventional tubes cannot be used at microwave frequencies i.e., > 100 MHz

1. Interelectrode capacitance effect
2. Lead inductance effect
3. Transit time effect
4. Gain-bandwidth limitation
5. Effect due to RF losses
6. Radiation losses.

1. **Interelectrode Capacitance Effect**

At low or medium frequencies, the interelectrode capacitances in a vacuum tube produce large capacitive reactances. Though they do not effect the tube operation, the frequency increases, with decrease in reactance, $X_C = \frac{1}{2\pi fC}$ ($\because X_C$ becomes almost a short circuit at higher frequencies). C_{gp}, C_{gk} and C_{pk} are the interelectrode capacitances which come into effect and are as shown in the figure.



Figure

Remedy: By reducing the inter electrode capacitances C_{gk}, C_{pk} and C_{gp}, the above effect can be minimized. These capacitances can be reduced by decreasing the area of electrodes i.e., increasing the distance between electrodes,

$$\therefore C = \frac{\varepsilon_0 \varepsilon_r}{d} A$$

2. **Lead Inductance Effect:** The voltage appearing at the active electrodes is less than the voltages at the base pins because the reactance, $X_L = 2\pi fL$ increases with an increase in frequency. Thus, the gain of the tube amplifier is reduced. The performance of the tube is limited by the lead inductances L_k, L_g and L_p as shown in figure.

Remedy: By decreasing the values of 'L_k and L_g', the above effect can be minimized. These inductances can be decreased by using larger sized short leads without base pins.

3. **Transit Time Effect:** The time taken for the electrons to travel from cathode to anode is known as transit time.

i.e., $\tau = d/v_0$ ... (1)

Where,

d – Distance between cathode and anode

v_0 – Electron velocity.

At low frequencies, transit time is negligible compared to the time period of the RF signal applied. Therefore, the plate current, i_p can instantaneously respond to the respective changes in grid voltage, V_g i.e., both i_p and V_g are in phase.

At high frequencies, i_p lags V_g and transconductance, g_m becomes a complex quantity (as the transit time is comparable with the period of the signal). Thus, the gain of the tube amplifier becomes complex even for resistive load, which results in reduced real gain values.

Remedy: By decreasing the separation between electrodes, transit time can be minimized, but this will increase the inter electrode capacitance effect. Therefore, trade-off is a must between interelectrode capacitance and transit time.

4. **Gain Bandwidth Limitation:** The gain-bandwidth product of a tuned circuit is given by,

$$\boxed{\text{Gain bandwidth product} = \frac{g_m}{C}}$$

Since, the gain bandwidth product is independent of supply frequency. Higher gain can be achieved at the cost of bandwidth, as g_m and C are fixed for a particular tube amplifier.

Remedy: This limitation can be overcome by using reentrant cavities and slow wave tubes over large bandwidths.

5. **Effect due to RF Losses**

RF losses in conventional tubes specifies two losses. They are,

(a) **Skin Effect Losses:** The current has a tendency to confine itself to a small cross-section of the conductor at higher frequencies. Thus, skin effect losses are introduced at these frequencies only.

Remedy: By increasing the size of the conductors, these losses can be reduced.

(b) **Dielectric Losses:** This type of loss occurs in spacers, glass envelope, silicon or plastic encapsulation type insulating materials. The power loss increases as the frequency of operation increases, i.e.,

$$\boxed{P = \pi f V_0^2 \varepsilon_r \tan\delta}$$

Where,

ε_r – Relative permittivity of the dielectric.

δ – Loss angle of the dielectric.

Remedy: These losses can be minimized by eliminating the tube base and reducing the surface area of the glass.

6. **Radiation Losses:** These losses occur when the dimensions of the wire approach the wavelength, which increases with increase in frequency.

Remedy: By using proper shielding for the tubes and circuitry, these losses can be minimized.

Q18. Show that input admittance of triode circuit is given by $\omega^2 L_K C_{gk} g_m + j\omega C_{gk}$, considering the interelectrode capacitances lead inductances.

Ans:

Figure (1) shows the circuit arrangement of a triode tube amplifier. In figure (1), the passive elements capacitance, inductance and resistance are associated with the triode plate, grid and cathode.

The admittance is of triode circuit obtained by considering only dominant values of inductance and capacitance in the low frequency triode equivalent model.

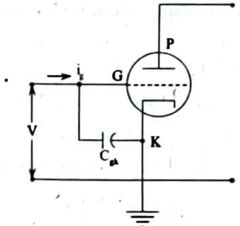


Figure (1)

The equivalent circuit of triode circuit is obtained by neglecting L_1, L_g, C_{gp} and C_{pk} as shown in figure (2).

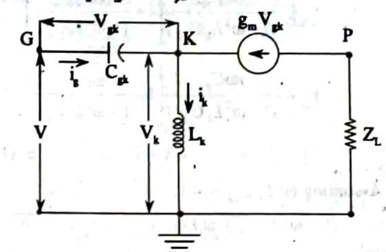


Figure (2)

At high frequencies, L_k and C_{gk} must be considered.

Applying KVL at the input side,

$$V = V_{gk} + V_k \quad \text{... (1)}$$

Applying KCL at the node 'K',

$$i_k = i_g + g_m V_{gk} \quad \text{... (2)}$$

But the voltage across the capacitor, C_{gk} is given by,

$$V_{gk} = i_g \cdot X_{C_{gk}} = \frac{i_g}{j\omega C_{gk}}$$

$$\Rightarrow \quad i_g = j\omega C_{gk} V_{gk} \quad \text{... (3)}$$

The voltage across the inductor L_k is given by,

$$V_k = i_k X_{L_K} = j\omega L_k i_k$$

$$i_k = \frac{V_k}{j\omega L_k}$$

Substituting the value of i_k in equation (2),

$$V_k = j\omega L_k (i_g + g_m V_{gk}) \quad \text{... (4)}$$

Substituting equation (4) in equation (1),

$$V = V_{gk} + j\omega L_k (i_g + g_m V_{gk})$$

$$= V_{gk} + j\omega L_k i_g + j\omega L_k g_m V_{gk}$$

$$= V_{gk} + j\omega L_k (j\omega C_{gk} V_{gk}) + j\omega L_k g_m V_{gk}$$

($\because$ From equation (3))

$$\Rightarrow \quad V = V_{gk} [1 + j\omega L_k g_m - \omega^2 L_k C_{gk}] \quad \text{... (5)}$$

The input admittance of the triode circuit is given by,

$$Y_{in} = \frac{i_g}{V}$$

From equations (3) and (5),

$$Y_{in} = \frac{j\omega C_{gk} V_{gk}}{V_{gk}[1 + j\omega L_k g_m - \omega^2 L_k C_{gk}]}$$

$$= \frac{j\omega C_{gk}}{(1-\omega^2 L_k C_{gk})\left[1 + \frac{j\omega L_k g_m}{1-\omega^2 L_k C_{gk}}\right]}$$

$$= \frac{j\omega C_{gk}}{(1-\omega^2 L_k C_{gk})}\left[1 + \frac{j\omega L_k g_m}{1-\omega^2 L_k C_{gk}}\right]^{-1}$$

$$Y_{in} = \frac{j\omega C_{gk}}{(1-\omega^2 L_k C_{gk})}\left[1 - \frac{j\omega L_k g_m}{1-\omega^2 L_k C_{gk}}\right].$$

$$[\because (1+x)^{-1} = 1 - x + x^2 - x^3 + \ldots\ldots \simeq (1-x)]$$

Assuming $\omega^2 L_k C_{gk} << 1$,

$\Rightarrow$ $(1 - \omega^2 L_k C_{gk}) \simeq 1$

Then,

$$Y_{in} = j\omega C_{gk}[1 - j\omega L_k g_m]$$

$$= j\omega C_{gk} + \omega^2 g_m L_k C_{gk}$$

$$\boxed{\therefore Y_{in} = \omega^2 g_m L_k C_{gk} + j\omega C_{gk}}$$

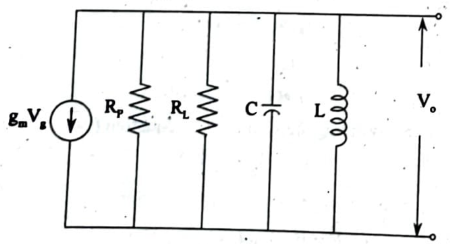
Hence proved.

Q19. Explain the gain bandwidth product limitation in conventional vacuum tubes.

Ans:

Figure shows the equivalent circuit of a vacuum tube amplifier. The transfer function for the circuit in figure is given by,

$$\text{Gain, } G = \frac{V_0(S)}{V_i(S)} = Z_0(S)$$



Figure

$$\text{Consider, } \frac{1}{Z_0(S)} = Y_0(S)$$

$$= CS + \frac{1}{LS} + \frac{1}{R_L} + \frac{1}{R_P}$$

(After applying laplace transform)

Replacing R_L and R_p by, $R = \frac{1}{R_L} + \frac{1}{R_P}$

$$\Rightarrow \quad \frac{1}{Z_0(S)} = CS + \frac{1}{LS} + \frac{1}{R}$$

$$= \frac{S^2 LCR + LS + R}{LSR}$$

$$\Rightarrow \quad Z_0(S) = \frac{RLS}{S^2 LCR + LS + R}$$

Dividing the numerator and denominator by LCR on R.H.S,

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

The denominator gives the characteristic equation, the roots of which gives the extreme frequencies ω_1 and ω_2.

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

$$\omega_2 = -\frac{G}{2C} + \sqrt{\left[\frac{G}{2C}\right]^2 - \frac{1}{LC}}$$

$$\text{Where, } G = \frac{1}{R}$$

Bandwidth, $BW = \omega_2 - \omega_1$

$$\Rightarrow BW = \left[-\frac{G}{2C} + \sqrt{\left[\frac{G}{2C}\right]^2 - \frac{1}{LC}}\right] - \left[-\frac{G}{2C} - \sqrt{\left[\frac{G}{2C}\right]^2 - \frac{1}{LC}}\right]$$

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

$$\text{Assuming } \left(\frac{G}{2C}\right)^2 >> \frac{1}{LC}$$

$$\text{Then, } BW = 2\sqrt{\left(\frac{G}{2C}\right)^2}$$

$$\Rightarrow \quad BW = \frac{G}{C}$$

But, the maximum gain is achieved, when the circuit is at resonance.

Then, Gain at resonance is given by,

$$A_{max} = \frac{g_m}{G}$$

$\therefore$ Gain bandwidth product $= A_{max} \cdot BW$

$$= \frac{g_m}{G} \cdot \frac{G}{C} = \frac{g_m}{C}$$

$\therefore$ The gain bandwidth product is independent of frequency.

1.1.2 Microwave Tubes – O-type and M-type Classifications

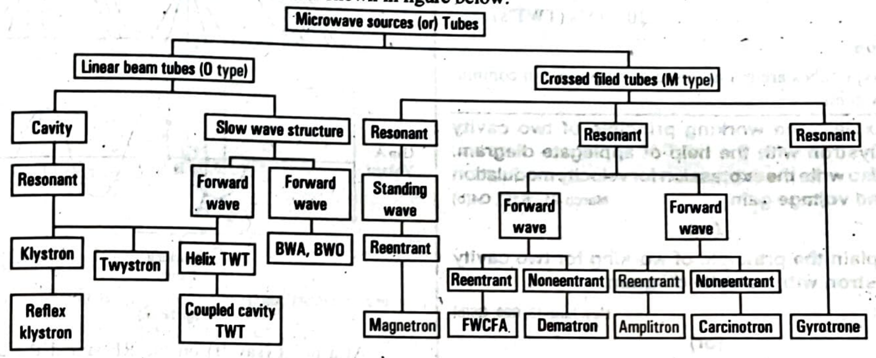
Q20. Classify the various microwave tubes with respect to the orientation of electric and magnetic fields.

Ans: April/May-18, (R13), Q7(a)

Microwave tubes are electron guns for generating electron beams. Microwave tubes not only generate but also amplify higher frequencies in the microwave range of frequency spectrum Microwave sources (or) tubes are broadly classified into two types. They are,

1. Linear beam tubes (O-type)
2. Crossed field tubes (M-type).

The classification of microwave sources is shown in figure below:



Figure

1. **Linear Beam Tubes (O-type):** O-tubes tubes are the microwave tubes in which the magnetic field is alone used for focussing of the electron beam i.e., the beam path is a straight line. Hence, these tubes are called linear beam tubes. O-type tubes are classified as,

   (i) Cavity type (ii) Slow wave structure.

2. **Crossed Field Tubes (M-type):** M-type tubes are the microwave tubes in which the electric and magnetic fields are prependicular to each other. Hence, these tubes are also known as cross field tubes. M-type tubes are classified as,

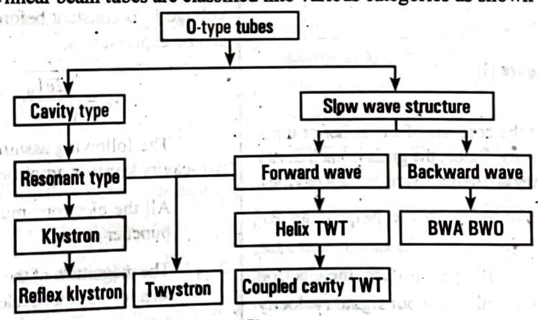
   (i) Negative resistance type
   (ii) Cyclotron frequency type
   (iii) Travelling wave (or) cavity type.

1.1.3 O-type Tubes: 2 Cavity Klystrons – Structures, Reentrant Cavities, Velocity Modulation Process and Applegate Diagram, Bunching Process and Small Signal Theory – Expressions for O/P Power and Efficiency

Q21. Classify O-Type tubes and mention their specifications and applications.

Ans:

Original tubes (O-tubes) or linear beam tubes are classified into various categories as shown in figure.



Figure

Specifications of O-type Tubes

1.	Peak output power	:	≈ 30 mW (maximum)
2.	Beam voltage	:	≈ 100 kV
3.	Frequency	:	10 GHz
4.	Average power output	:	700 kW (maximum)
5.	Gain	:	30 – 70 dB
6.	Efficiency	:	15 – 60%
7.	Bandwidth	:	1 – 8% (klystron) 10 – 15% (TWT's)

Application

O-type tubes are mainly used as amplifiers in communication systems.

Q22. Explain the working principle of two cavity Klystron with the help of applegate diagram. Also write the expression for velocity modulation and voltage gain. March-21, (R16), Q4(b)

(or)

Explain the principle of working for two cavity klystron with velocity diagram. May/June-13, R09, Q6(b)

(or)

Explain the principle of a two cavity klystron with a neat diagram. Nov.-13, (R09), Q5(a)

Ans:

Two-cavity Klystron Amplifier

A two-cavity klystron tube is a linear beam type microwave amplifier which works on the principle of velocity modulation. The construction of two-cavity klystron amplifier is as shown in figure (1).

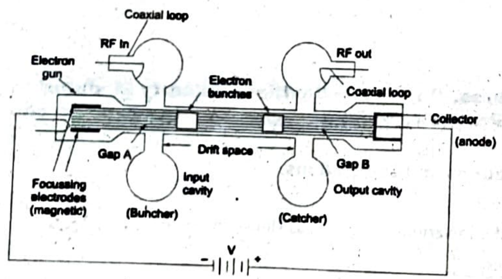


Figure (1)

Construction

In figure (1), klystron tube consists of a buncher or input cavity and catcher or output cavity. Since, the grids in each cavity are separated by a small gap they are named as re-entrant cavities.

The input cavity is excited with the help of an RF signal. The electron beam is injected into the tube reaches the gap between input cavity grids(drift space). Here, the electron velocity is varies in accordance with the input signal (velocity modulation).

Working

When the RF signal is applied to the input buncher cavity, it develops an alternating voltage across the gap A. The effect of this gap voltage on the electron beam (velocity modulation) can be explained by applegate diagram as shown in figure (2).

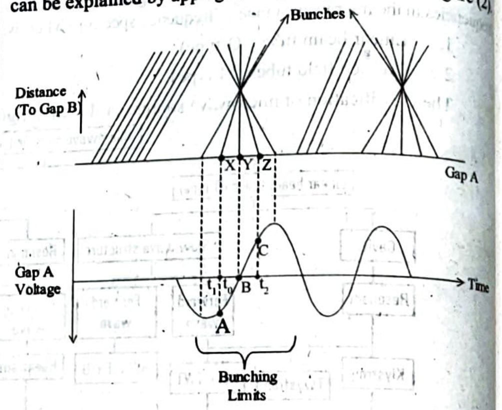


Figure (2)

At a point (say B) on the RF signal the alternating voltage is zero and going positive with the electric field across the gap A as zero. The electron which passes through the gap A is unaffected by the RF signal. Assuming this as the reference electron Y. Another electron Z, passes the gap slightly later than Y.

At a point C, the late electron Z subjected to maximum positive RF voltage. As a result, this electron travels towards gap B with an increased velocity and tries to catch up with the reference electron. Similarly, an electron X called the early electron passes the gap A slightly before the reference electron is subjected to a maximum negative RF voltage. Therefore, this electron X travels with a reduced velocity and falls back, and the reference electron Y catches up with the early electron.

This shows that the changes in velocity of electron in accordance with the RF voltage results in velocity modulation of the electron beam.

The velocity of electrons accelerated by the high D.C. voltage V_0 is constant before entering the buncher grids and it can be expressed as,

$$v_0 = \sqrt{\frac{2eV_0}{m}} \quad \text{... (1)}$$

The following assumptions are made in the analysis of two-cavity klystron amplifier,

1. All the electrons must be passed through the mesh of buncher cavity.
2. The magnitude of the microwave signal input, V_1 is much smaller than the accelerating D.C voltage, V_0 i.e., $V_1 << V_0$.
3. The effects of space charge are negligible.

Then, The force exerted in the electric field, E is given by,

$$F = ma = -eE \quad \text{... (2)}$$

$$\Rightarrow \quad a = \frac{-e}{m}E$$

Assume that, the electrons are propagating in 'Z' direction.

$$\text{Then, } \frac{d^2z}{dt^2} = \frac{-e}{m}E_z \quad \left[\because a = \frac{d^2z}{dt^2}\right] \quad \text{... (3)}$$

The instantaneous gap voltage, V_g is given by,

$$V_g = V_1 \sin\omega t$$

The field intensity, $E_z = \dfrac{-V_g}{d}$

$$E_z = \frac{-V_1 \sin\omega t}{d} \quad \text{... (4)}$$

Where,

d – Drift spacing between the two cavities

Substituting equation (4) in equation (3),

$$\frac{d^2z}{dt^2} = \frac{e}{m}\frac{V_1 \sin\omega t}{d}$$

Integrating above equation in the interval 't_0' and 't_1' at which the electron enters the buncher cavity,

$$\frac{dz}{dt} = \frac{eV_1}{m}\int_{t_1}^{t_0} \sin\omega t\, dt$$

$$\frac{dz}{dt} = \frac{eV_1}{md}(-\cos\omega t)\Big|_{t_1}^{t_0}$$

$$\Rightarrow \quad \frac{dz}{dt} = \frac{eV_1}{md}\frac{[\cos\omega t_1 - \cos\omega t_0]}{\omega} + C \quad \text{... (5)}$$

At $t_0 = t_1$, the electron enters the cavity with velocity v_0,

$$\Rightarrow \quad \frac{dz}{dt}\Big|_{t_0 = t_1} = C = v_0$$

Rearranging equation (5), we get,

$$\frac{dz}{dt} = v_0 - \frac{eV_1}{md}\frac{[\cos\omega t_0 - \cos\omega t_1]}{\omega} \quad \text{... (6)}$$

Equation (6) gives the velocity of the electrons, as long as they are within the cavity gap 'd'.

Consider 't_2' as the time at which the electron leaves the gap. Then, the corresponding velocity, $v(t)$ is given by,

$$v(t) = v_0 - \frac{eV_1}{m\omega d}[\cos\omega t_2 - \cos\omega t_1] \quad \text{... (7)}$$

As the D.C voltage, V_0 is very larger than the applied input signal voltage, V_1, the electron transit time t_1 and t_2 are obtained as,

As $V_1 << V_0$,

$$t_1 = t_0 - \frac{d}{2v_0}$$

$$t_2 = t_0 + \frac{d}{2v_0}$$

Equation (7) can be written as,

$$v(t) = v_0 - \frac{eV_1}{m\omega d}\left[\cos\omega\left(t_0 + \frac{d}{2v_0}\right) - \cos\omega\left(t_0 - \frac{d}{2v_0}\right)\right]$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{m\omega d}\left[2\sin\omega t_0 \sin\frac{\omega d}{2V_0}\right]$$

$$[\because \cos(A + B) - \cos(A - B) = -2\sin A \sin B]$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{mv_0}\frac{\sin\left[\frac{\omega d}{2v_0}\right]}{\left[\frac{\omega d}{2v_0}\right]}\sin\omega t_0$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{mv_0}\beta_i \sin\omega t_0$$

Where,

β_i – Beam coupling coefficient.

$$\beta_i = \frac{\sin\left(\frac{\omega d}{2v_0}\right)}{\frac{\omega d}{2v_0}}$$

$$\Rightarrow \quad v(t) = v_0\left[1 + \frac{eV_1}{mv_0^2}\beta_i \sin\omega t_0\right]$$

$$\Rightarrow \quad v(t) = v_0\left[1 + \frac{V_1}{2V_0}\beta_i \sin\omega t_0\right] \quad \left[\because v_0^2 = \frac{2eV_0}{m}\right]$$

Excitation ratio, $\alpha = \dfrac{V_1}{V_0}$

$$\boxed{\therefore v(t) = v_0\left[1 + \frac{\alpha\beta_i}{2}\sin\omega t_0\right]}$$

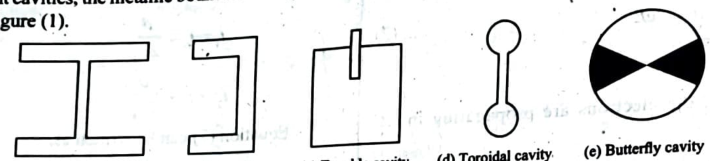
Q23. Explain Reentrant cavities.

Ans:

A cavity with the metallic boundaries penetrating into its interior is known as "Reentrant Cavity". The devices can provide a very sensitive high-Q microwave mode. The design of reentrant cavities can be highly advantage for electromechanical devices and quantum measurements.

A Cavity Resonator acts as a lumped constant resonant circuit for a frequency range less than the microwave range. For increased values of operating frequency (upto Mega Hertz), it is observed that the inductance and capacitance values are decreased to an extent. This a resonance in the circuit at the new frequency. However the Reduction in the inductance value is obtained using a short - wire. Hence, these reentrant cavities are designed for their application in klystrons and microwave triodes.

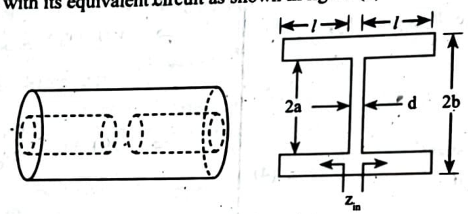
In reentrant cavities, the metallic boundaries are extended into the interior of cavity. Some of the shapes of reentrant cavities are as shown in figure (1).



(a) Coaxial cavity (b) Radial cavity (c) Tunable cavity (d) Toroidal cavity (e) Butterfly cavity

Figure (1): Reentrant Cavities

Consider a coaxial cavity with its equivalent circuit as shown in figure (2).



(a) Coaxial cavity **(b) Equivalent Circuit of Coaxial Cavity**

Figure (2)

Coaxial cavity resembles a coaxial line shorted at two ends and joined by a capacitor at the center.

It's input impedance is given by,

$$Z_{in} = jZ_0 \tan(\beta l) \quad \text{... (1)}$$

Where,

l – Length of coaxial line

The characteristic impedance of a coaxial line is given by,

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{b}{a}\right) \quad \text{... (2)}$$

Substituting equation (2) in equation (1), we get,

$$Z_{in} = j\frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{b}{a}\right)\tan\beta l$$

But, inductance of cavity is given by,

$$L = \frac{2X_{in}}{\omega} = \frac{1}{\pi\omega}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{b}{a}\right)\tan(\beta l)$$

and capacitance, $C_g = \dfrac{\varepsilon\pi a^2}{d}$

At resonance, $\omega L = \dfrac{1}{\omega C_g}$

$$\Rightarrow \frac{\omega}{\pi\omega}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{a}{b}\right)\tan\beta l = \frac{a}{\omega\varepsilon\pi a^2}$$

$$\Rightarrow \tan\beta l = \frac{d}{\omega E a^2\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{a}{b}\right)}$$

$$\therefore \tan\beta l = \frac{Vd}{\omega a^2 \ln\left(\frac{b}{a}\right)}$$

Where, $V = \dfrac{1}{\sqrt{\mu\varepsilon}}$

Consider a radial resonant cavity as shown in figure (3).

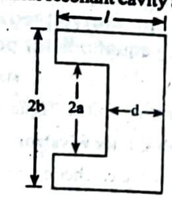


Figure (3)

Here,

$$L = \frac{\mu l}{2\pi}\ln\left(\frac{b}{a}\right)$$

$$C = \varepsilon_0\left[\frac{\pi a^2}{d} - 4a\ln\frac{0.765}{\sqrt{l^2+(b-a)^2}}\right]$$

The resonant frequency of radial reentrant cavity is given by,

$$f_r = \frac{C}{2\pi\sqrt{\varepsilon_r}}\left\{al\left[\frac{a}{2d} - \frac{2}{l}\ln\frac{0.765}{\sqrt{l^2+(b-a)^2}}\right]\ln\left(\frac{b}{a}\right)\right\}^{-1/2}$$

Q24. Compose and explain about two cavity Klystron amplifier and derive its Bunching process.

Oct./Nov.-20, (R16), Q5(a)

(or)

With the help of Applegate diagram, explain the bunching process and hence the velocity modulation in Klystron amplifier.

April/May-18, (R13), Q6(a)

(or)

Explain in detail bunching process and obtain expression for bunching parameter in a two cavity klystron. Nov./Dec.-16, (R13), Q6

(or)

Discuss in detail bunching process for a two cavity klystron amplifier and obtain the expression for bunching parameter.

Nov./Dec.-12, (R09), Q5(b)

Ans:

For answer refer Unit-1, Q22, Topic: Two-cavity Klystron Amplifier, Construction, working.

Bunching Process

In a two cavity klystron amplifier, the electrons leave the buncher cavity, with a velocity given by,

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

This effect of velocity modulation produces an electron beam, which passes through the buncher cavity at three possibilities. They are,

1. When the voltage is zero
2. When the voltage is positive
3. When the voltage is negative.

In a klystron amplifier, electron bunching is formed due to the propagation of electrons with different velocities. The electron beam coming from the cathode is a effected by input RF voltage applied at the buncher cavity. At zero RF voltage, the electron moves with its actual velocity v_0 and becomes the bunching center. For a maximum positive voltage, the electron accelerates with a velocity greater than v_0. In the same manner, the electron that passes the cavity at maximum negative voltage decelerates with the velocity less than v_0.

The beam electrons drifted into dense clusters with a separation gap of ΔL along the input wave as shown in figure below.

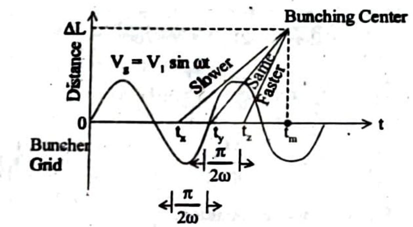


Figure: Bunching Process

The distance of an electron at 't_y' from the buncher grid to the location of dense electron bunching is given by,

$$\Delta L = v_0(t_m - t_y) \quad \text{... (1)}$$

Similarly, the distances for the electrons at 't_x' and 't_z' are,

$$\Delta L = v_{min}(t_m - t_x) = v_{min}\left(t_m - t_y + \frac{\pi}{2\omega}\right) \quad \text{... (2)}$$

$$\Delta L = v_{max}(t_m - t_z) = v_{max}\left(t_m - t_y - \frac{\pi}{2\omega}\right) \quad \text{... (3)}$$

From the expression $v(t)$, the minimum and maximum velocities are obtained as,

$$v_{min} = v_0\left[1 - \frac{\beta_i V_1}{2V_0}\right] \quad \left[\because t_1 = -\frac{\pi}{2\omega}, \theta_g \simeq 0\right] \quad \text{... (4)}$$

$$v_{max} = v_0\left[1 + \frac{\beta_i V_1}{2V_0}\right] \quad \left[\because t_1 = \frac{\pi}{2\omega}, \theta_g \simeq 0\right] \quad \text{... (5)}$$

Substituting equation (4) in equation (2),

$$\Delta L = v_0\left[1 - \frac{\beta_i V_1}{2V_0}\right]\left[(t_m - t_y) + \frac{\pi}{2\omega}\right]$$

$$= v_0(t_m - t_y) + \left[v_0\frac{\pi}{2\omega} - v_0\frac{\beta_i V_1}{2V_0}(t_m - t_y) - v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \quad \text{... (6)}$$

Substituting equation (5) in equation (3),

$$\Delta L = v_0\left[1 + \frac{\beta_i V_1}{2V_0}\right]\left[(t_m - t_y) - \frac{\pi}{2\omega}\right]$$

$$= v_0(t_m - t_y)\left[-v_0\frac{\pi}{2\omega} + V_0\frac{\beta_i V_1}{2V_0}(t_m - t_y) + v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right] \quad \text{... (7)}$$

Then, the necessary condition for those electrons at t_s, t_y and t_z to meet at the same distance, ΔL is,

$$v_0\frac{\pi}{2\omega} - v_0\frac{\beta_i V_1}{2V_0}(t_m - t_y) - v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega} = 0 \quad \text{... (8)}$$

(or)

$$-v_0\frac{\pi}{2\omega} + v_0\frac{\beta_i V_1}{2V_0}(t_m - t_y) + v_0\frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega} = 0$$

$$\Rightarrow v_0\left(\frac{\pi}{2\omega} - \frac{\beta_i V_1}{2V_0}(t_m - t_y) - \frac{\beta_i V_1}{2V_0}\frac{\pi}{2\omega}\right) = 0$$

$$\Rightarrow \frac{\pi}{2\omega} = \frac{\beta_i V_1}{2V_0}\left(t_m - t_y - \frac{\pi}{2\omega}\right)$$

$$\Rightarrow t_m - t_y = \frac{\pi}{2\omega}\left(\frac{2V_0}{\beta_i V_1} - 1\right)$$

$$t_m - t_y = \frac{\pi V_0}{\omega \beta_i V_1} \qquad [\because V_0 >> V_1]$$

From the above condition,

$$(t_m - t_y) \simeq \frac{\pi V_0}{\omega \beta_i V_1} \quad \text{... (9)}$$

By substituting equation (9) in equation (1), the expression for minimum distance at which bunching occurs is obtained as,

$$\boxed{\Delta L = v_0 \frac{\pi V_0}{\omega \beta_i V_1}}$$

The transit time for an electron to travel a distance 'L' is,

$$T = t_2 - t_1 = \frac{L}{v(t_1)}$$

$$\therefore T = T_0\left[1 - \frac{\beta_i V_1}{2V_0}\sin\left(\omega t_1 - \frac{\theta_g}{2}\right)\right] \quad \left[\because T_0 = \frac{L}{v_0}\right]$$

This can be expressed in terms of radians as,

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

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

Here, $\frac{\omega L}{v_0}$ is replaced by θ_0 and $\frac{\beta_i V_1}{2V_0}\theta_0$ is replaced by 'X'.

Where,

X – Bunching parameter of a klystron

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

Q25. Explain the bunching process of two cavity klystron amplifier with Applegate diagram and also derive the equations for power efficiency.

May/June-19, (R15), Q6

Ans:

For answer refer Unit-1, Q24, Topic: Bunching Process.

Output Power of a two Cavity Klystron

The RF voltage at the catcher cavity is given by,

RF voltage = $V_2 \sin\omega t_2$

Where,

t_2 – Time taken by electron to reach catcher.

Then, the energy given by the electron to the bunch is,

$$E = (-e)V_2 \sin\omega t_2$$

Where,

e – Charge associated with the electron.

The average energy (i.e., power) applied to the RF field is given as,

$$P_{avg} = \frac{1}{2\pi}\int_0^{2\pi}(-eV_2\sin\omega t)\,d(\omega t_1) \quad \text{... (1)}$$

If 't_1' is time taken by electron to reach buncher cavity and 't_2' is the time at which electron leaves the cavity gap, then the transit time (T) for velocity modulated electron in the field free space between cavities is given by,

$$T = t_2 - t_1$$

If 'L' is the distance between the buncher and catcher cavity and the electron is travelling with a velocity v_1.

Then, $T = t_2 - t_1 = \frac{L}{v_1}$

From the concept of velocity modulation,

$$v_1 = v_0\sqrt{\left[1 + \frac{V_1}{V_0}\right]\sin\omega t_1}$$

Where,

V_1 – RF voltage in buncher cavity

V_0 – DC voltage.

$$\Rightarrow T = t_2 - t_1 = \frac{L}{v_0\left[\left(1 + \frac{V_1}{V_0}\right)\sin\omega t_1\right]^{1/2}}$$

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

$$= \frac{L}{v_0}\left[1 - \frac{V_1}{2V_0}\sin\omega t_1\right]$$

[$\because (1+a)^{-1/2} = 1 - a/2$, neglecting higher order terms for $a < 1$]

Multiplying with 'ω' on both sides, we get,

$$\omega T = \omega(t_2 - t_1) = \frac{\omega L}{v_0}\left[1 - \frac{V_1}{2V_0}\sin\omega t_1\right] \quad \text{... (2)}$$

From equation (2),

$$\omega t_2 = \omega t_1 + \frac{\omega L}{v_0}\left[1 - \frac{V_1}{2V_0}\sin\omega t_1\right]$$

Substituting the value of ωt_2 in equation (1),

$$P_{avg} = \frac{1}{2\pi}\int_0^{2\pi} -eV_2 \sin\left[\omega t_1 + \frac{\omega L}{v_0}\left[1 - \frac{V_1}{2V_0}\sin\omega t_1\right]\right] d(\omega t_1)$$

$$\Rightarrow P_{avg} = \frac{1}{2\pi}\int_0^{2\pi} -eV_2 \sin\left[\omega t_1 + \theta_0\left(1 - \frac{V_1}{2V_0}\sin\omega t_1\right)\right] d(\omega t_1) \quad \text{... (3)}$$

Where,

T_0 – Transit time without RF voltage $V_1 = \frac{L}{v_0}$

θ_0 – Transit angle without RF voltage $V_1 = \frac{\omega L}{v_0}$

Equation (3) represents a Bessel function and its solution is given as,

$$P_{avg} = -eV_2 J_1(X)\sin\theta_0$$

Where,

$J_1(X)$ – Bessel function of first order for the argument 'X'.

Assuming 'N' number of electrons moving from buncher to catcher cavity, then the average energy associated is given as,

$$P'_{avg} = NP_{avg}$$

$$= -NeV_2 J_1(X)\sin\theta_0$$

$$P'_{avg} = -I_o V_2 J_1(X)\sin\theta_0$$

Where,

I_o – Output current (Ne).

The maximum value of output power is given by,

$$P_{max} = [J_1(X)]_{max} I_o V_2$$

$$\left[\because \sin\theta_0 = -1, \text{ where, } \theta_0 = 2n\pi - \frac{\pi}{2}\right]$$

$[J_1(X)]_{max}$ value is 0.58 for $X = 1.84$ from the Bessel function table.

Hence, $P_{out} = P_{max} = (0.58)I_o V_2$

$$\therefore \boxed{P_{out} = 0.581\, I_o V_2}$$

Efficiency of a Two Cavity Klystron: The efficiency of a two cavity klystron is defined as,

$$\eta = \frac{P_{out}}{P_{in}}$$

The expression for D.C input power, P_{in} is given by,

$$P_{in} = I_o V_0$$

Where,

V_o – Anode voltage

I_o – Output current

The output power, P_{out} of amplifier is given as,

$$P_{out} = 0.58\, I_o V_2$$

$$\text{Hence, } \eta = \frac{P_{out}}{P_{in}} = \frac{0.58 I_0 V_2}{I_0 V_0} = \frac{0.58 V_2}{V_0}$$

$$\eta = 0.58\left(\frac{V_2}{V_0}\right)$$

$$\Rightarrow \%\eta = \frac{0.58 V_2}{V_0} \times 100$$

$$\boxed{\therefore \%\eta = \frac{58 V_2}{V_0}}$$

Since, V_2 is always less than V_0, the maximum possible efficiency of klystron amplifier is 58% i.e., when $V_2 = V_0$.

The efficiency also depends on the transit angle values and is maximum for an angle of '$-\pi/2$' and zero for an angle of '2π'.

Q26. Write short notes on "two cavity klystron oscillator".

Ans:

The two-cavity klystron oscillator is obtained by simply providing a feedback loop between the input and output cavities of a two-cavity klystron amplifier is as shown in figure.

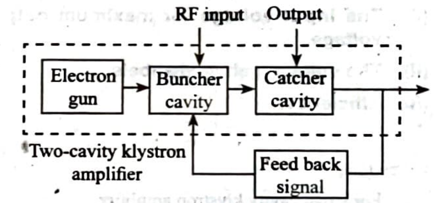


Figure: Block Diagram Representation of a Two-Cavity Klystron Oscillator

This oscillator must satisfy Barkhausen criterion. Depending on the cavity tuning and the various D.C. voltages, the feedback path between two cavity resonators is properly matched. The conditions for sustained oscillations are,

$$\boxed{\theta + \alpha + \frac{\pi}{2} = 2\pi n \text{ radians}} \quad \text{... (1)}$$

And gain-bandwidth product($A\beta$) = 1

Where,

θ – Total phase shift in the resonators and the feedback cable.

$\alpha + \frac{\pi}{2}$ – Phase angle between buncher and catcher voltages

n – integer.

If the two resonators oscillate in phase i.e., $\theta = 0$, then the maximum output power is obtained at the output of oscillator.

Substituting $\theta = 0$ in equation (1),

$$\boxed{\alpha = 2\pi n - \frac{\pi}{2}} \quad \text{... (2)}$$

The above condition is also necessary for obtaining the sustained oscillations.

If the resonators are over coupled, the oscillations can be obtained over wide range. Whereas a linear variation in frequency with accelerating voltage is possible for a critically coupled klystron oscillator. The high frequency stability of oscillator is obtained by,

1. Controlling the temperature of the resonators.
2. Use of regulated power supplies.

Advantages of Two-cavity Klystron Oscillator

1. It is the lowest-noise microwave source.
2. Two-cavity klystron oscillator generates more power than reflex klystron oscillator.
3. It requires only one high-voltage supply.

Application: This oscillator is used in the illuminator systems of missile targeting radars.

Q27. A two cavity klystron amplifier has the following parameters.

V_o = 1200 V, I_o = 25 mA, R_o = 30 kΩ, f = 10 GHz, d = 1 mm, L = 4 cm, R_{sh} = 30 kΩ.

Calculate,

(i) The input voltage for maximum output voltage.

(ii) The voltage gain in decibels.

(iii) Efficiency.

Ans:

Given that,

For a two cavity klystron amplifier,

$V_o = 1200$ V

$I_o = 25$ mA

$R_o = 30$ kΩ

$f = 10$ GHz

$d = 1$ mm

$L = 4$ cm

$R_{sh} = 30$ KΩ

(i) Input voltage for maximum output voltage, $V_{1(max)} = ?$

(ii) Voltage gain in dB, $A_v = ?$

(iii) Efficiency, $\eta = ?$

(i) The input voltage applied at two cavity klystron is given by,

$$V_i = \frac{2XV_0}{\beta_i\theta_0} \quad \dots (1)$$

Where,

X – Bunching parameter

V_o – D.C. voltage between anode and cathode

θ_o – Transit angle without RF voltage

β_i – Beam coupling coefficient

For maximum output power, $X = 1.84$

And, $\theta_0 = \frac{\omega L}{v_0}$

$$= \frac{2\pi f \times L}{0.593\times10^6\sqrt{V_0}} \quad [\because v_0 = 0.593\times10^6\sqrt{V_0}]$$

$$= \frac{2\pi\times10\times10^9\times4\times10^{-2}}{0.593\times10^6\sqrt{1200}}$$

$$= 122.347 \text{ rad} \simeq 122.35 \text{ rad}$$

i.e., D.C. transit angle, θ_0 = 122.35 rad

Beam coupling coefficient is given by,

$$\beta_i = \frac{\sin\frac{\theta_g}{2}}{\frac{\theta_g}{2}}$$

Where, θ_g = Average gap transit angle = $\frac{\omega d}{v_0}$

$$\theta_g = \frac{2\pi\times10\times10^9\times10^{-3}}{0.593\times10^6\sqrt{1200}} = 3.059 \text{ rad}$$

Then,

$$\beta_i = \frac{\sin\frac{\theta_g}{2}}{\frac{\theta_g}{2}} = \frac{\sin(3.059/2)}{3.059/2} = 0.653$$

On substituting corresponding values in equation (1),

$$V_{1(max)} = \frac{3.68\times1200}{0.653\times122.35} = 55.273 \text{ V}$$

$$\boxed{\therefore V_{1(max)} = 55.273 \text{ V}}$$

(ii) Voltage gain, A_v is given by,

$$A_v = \frac{V_2}{V_{1(max)}} \quad \dots (2)$$

Where,

$V_2 = \beta_0 I_2 R_{sh}$

$\Rightarrow I_2 = 2I_0J_1(X)$

For, $X = 1.84$

$J_1(X) = 0.582$ (From Bessel function table)

$\therefore I_2 = 2 \times 25 \times 10^{-3} \times 0.582$

$= 29.1$ mA

Then, $V_2 = \beta_0 I_2 R_{sh}$

$= \beta_i I_2 R_{sh} \quad [\because \beta_0 = \beta_i]$

$\therefore V_2 = 0.653 \times 29.1 \times 10^{-3} \times 30 \times 10^3$

$= 570.069$ V

On substituting corresponding values in equation (2),

$$A_v = \frac{570.069}{55.273} = 10.314$$

A_v(dB) = 20 log (10.314) = 20.269 dB

$$\boxed{\therefore A_v = 20.269 \text{dB}}$$

(iii) The expression for efficiency is given by, $\eta = \frac{J_1(X)V_2}{V_0}$

On substituting corresponding values in above equation,

$$\eta = \frac{0.582\times570.069}{1200} = 0.276 = 27.6\%$$

$$\boxed{\therefore \eta = 27.6\%}$$

Q28. In a two-cavity klystron the parameters are, input power = 10 mW, voltage gain = 20 dB, R_{sh} of input cavity = 25 KΩ, R_{sh} of output cavity = 35 KΩ, load resistance = 40 KΩ. Find input voltage, output voltage and the power to the load.

Ans: (Model Paper, Q2(b) | Nov./Dec.-17, (R13), Q6(b))

Given that,

For a two cavity klystron,

Input power, $P_{in} = 10$ mW

Voltage gain, $A_v = 20$ dB

R_{sh} of input cavity, $R_{sh(input)} = 25$ kΩ

R_{sh} of output cavity, $R_{sh(output)} = 35$ kΩ

Load resistance, $R_L = 40$ kΩ

Input voltage, $V_i = ?$

Output voltage, $V_o = ?$

Power delivered to the load, $P_{out} = ?$

Then, the expression for input voltage of a two cavity klystron is given by,

Input voltage, $V_i = \sqrt{(P_{in})R_{sh(input)}}$

$$= \sqrt{(10\times10^{-3})\times(25\times10^3)}$$

$$= \sqrt{10\times25} = \sqrt{250} = 15.81 \text{ V}$$

$$\boxed{\therefore V_i = 15.81 \text{ V}}$$

And the expression for output voltage of a two cavity klystron is given by,

Output voltage, $V_o = (A_v)V_i$

$$20 \log_{10}\frac{V_o}{V_i} = 20$$

$$\Rightarrow \log_{10}\frac{V_o}{V_i} = 1$$

$$\Rightarrow \frac{V_o}{V_i} = (10)^1$$

$$\Rightarrow V_o = 15.81 \times 15.81 \times 10 = 158.1 \text{ V}$$

$$\boxed{\therefore V_0 = 158.1 \text{ V}}$$

And the expression for power delivered to the load in two cavity klystron is given by,

$$\text{Power delivered to the load, } P_{out} = \frac{V_o^2}{R_{sh(output)}} = \frac{(158.1)^2}{35\times10^3}$$

$$= 714.16\times10^{-3} = 714.16 \text{mW}$$

$\therefore$ Power delivered to load, $P_{out} = 714.16$ mW.

Q29. The parameters of a two cavity klystron are given by V_b = 900 V, f = 3.2 GHz and d = 10^{-3} m. Determine electron velocity, transit angle and beam coupling coefficient.

Ans: (Nov./Dec.-16, (R13), Q7(a) | Dec.-14, (R09), Q5(b))

Given that,

For a two cavity klystron,

Beam voltage, $V_b = 900$ V

Frequency, $f = 3.2$ GHz

Drift spacing, $d = 10^{-3}$ m

Electron velocity, $v_o = ?$

Transit angle, $\theta_g = ?$

Beam coupling coefficient, $\beta_1 = \beta_2 = ?$

Then the electron velocity can be calculated by using the following relation,

$$v_o = 0.593 \times 10^6\sqrt{V_b} = 0.593 \times 10^6\sqrt{900}$$

$$= 17.79 \times 10^6$$

$$\boxed{\therefore v_o = 17.79\times10^6 \text{ m/s}}$$

and the expression for transit angle is given by,

$$\theta_g = \frac{\omega d}{V_o} = \frac{2\pi\times3.2\times10^9\times10^{-3}}{17.79\times10^6} = 1.13 \text{ rad}$$

$$\boxed{\therefore \theta_g = 1.13 \text{ rad}} \text{ or } \boxed{\theta_g = 64.744°}$$

and the expression for the beam coupling coefficient is given by,

$$\beta_1 = \beta_2 = \beta_2 = \frac{\sin\frac{\theta_g}{2}}{\frac{\theta_g}{2}} = \frac{\sin(32.372)}{1.13/2} = \frac{0.535}{0.565} = 0.947$$

$$\boxed{\therefore \beta_1 = \beta_2 = 0.947}$$

1.1.4 Reflex Klystrons – Structure. Velocity Modulation and Applegate Diagram, Mathematical Theory of Bunching, Power Output, Efficiency, Oscillating Modes and O/P Characteristics

Q30. Explain briefly about the construction and operation of reflex klystron oscillator.

Nov.-15, (R09) Q5(b)

(or)

What is reflex klystron. Explain its operation with a neat diagram. May/June-13, R09, Q5(a)

Ans:

Reflex klystron is a linear beam type microwave amplifier, which works on the principle of velocity modulation. It is used in microwave measurements and microwave receivers as local oscillators. Figure (1) shows the schematic diagram of a reflex klystron.

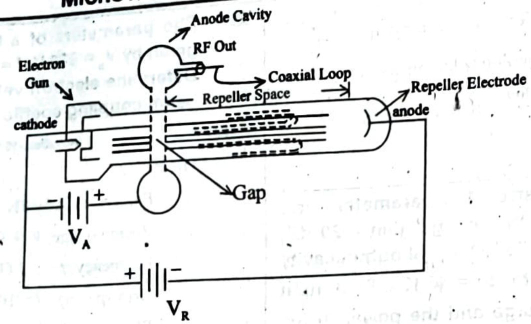


Figure (1): Construction of Reflex Klystron

Construction: The reflex klystron consists of electron gun, filament surrounded by a cathode and focusing electrode at cathode potential. The electron beam is emitted from the cathode and is accelerated by the grid G. This beam is passed through the anode cavity to the repeller space between the anode cavity and repeller electrode.

Operation: The electron beam from the cathode is velocity modulated by the cavity gap voltage. Due to this, some of the electrons accelerate and enter the repeller space with a greater velocity, while some of them decelerate and enter the repeller space with less velocity. In the repeller region, all the electrons are bunched together and pass through the cavity gap for every cycle. On the return path i.e., during retarding phase, the bunched electrons pass through the gap and deliver the kinetic energy to the electromagnetic energy of the field in the anode cavity. The output is taken from the anode cavity.

The analysis of a reflex klystron is similar to that of a two-cavity klystron. Figure(2) illustrates the apple gate diagram for $1\frac{3}{4}$ mode of reflex klystron.

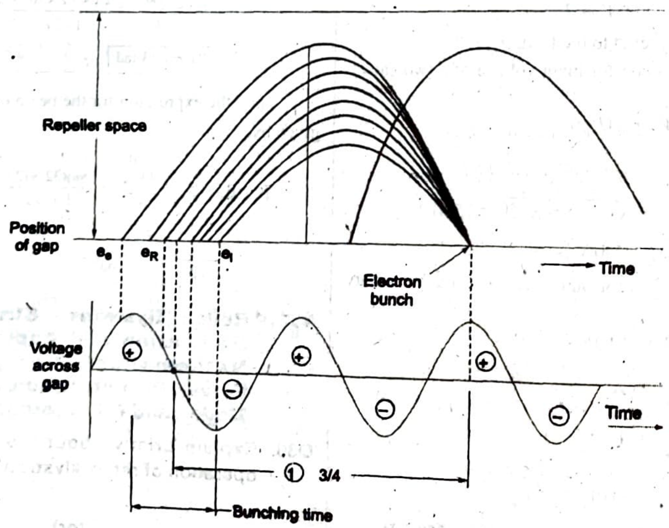


Figure (2): Applegate Diagram

The uniform velocity with which the electrons enter into the cavity is given as,

$$v_0 = \sqrt{\frac{2eV_0}{m}} = 0.593 \times 10^6 \sqrt{V_0} \text{ m/s} \quad \dots (1)$$

Then, The force exerted in the electric field, E is given by,

$$F = ma = -eE$$

$$\Rightarrow \quad a = \frac{-e}{m}E \quad \dots (2)$$

Assume that, the electrons are propagating in 'Z' direction.

$$\text{Then, } \frac{d^2z}{dt^2} = \frac{-e}{m}E_z \quad \left[\because a = \frac{d^2z}{dt^2}\right] \quad \dots (3)$$

The instantaneous gap voltage, V_g is given by,

$$V_g = V_1 \sin\omega t.$$

$$\text{The field intensity, } E_z = \frac{-V_g}{d}$$

$$E_z = \frac{-V_1 \sin\omega t}{d} \quad \dots (4)$$

Where,

d – Drift spacing between the two cavities

Substituting equation (4) in equation (3),

$$\frac{d^2z}{dt^2} = \frac{e}{m}\frac{V_1 \sin\omega t}{d}$$

Integrating above equation in the interval 't_0' and 't_1' at which the electron enters the buncher cavity,

$$\frac{dz}{dt} = \frac{eV_1}{m}\int_{t_1}^{t_0} \sin\omega t \, dt$$

$$\frac{dz}{dt} = \frac{eV_1}{md}(-\cos\omega t)\Big|_{t_1}^{t_0}$$

$$\Rightarrow \quad \frac{dz}{dt} = \frac{eV_1}{md}\frac{[\cos\omega t_1 - \cos\omega t_0]}{\omega} + C \quad \dots (5)$$

At $t_0 = t_1$, the electron enters the cavity with velocity v_0,

$$\Rightarrow \quad \frac{dz}{dt}\Big|_{t_0 = t_1} = C = v_0$$

Rearranging equation (5), we get,

$$\frac{dz}{dt} = v_0 - \frac{eV_1}{md}\frac{[\cos\omega t_0 - \cos\omega t_1]}{\omega} \quad \dots (6)$$

Equation (6) gives the velocity of the electrons, as long as they are within the cavity gap 'd'.

Consider 't_2' as the time at which the electron leaves the gap. Then, the corresponding velocity, $v(t)$ is given by,

$$v(t) = v_0 - \frac{eV_1}{m\omega d}[\cos\omega t_2 - \cos\omega t_1] \quad \dots (7)$$

As the D.C voltage, V_0 is very larger than the applied input signal voltage, V_1, the electron transit time t_1 and t_2 are obtained as,

As $V_1 << V_0$

$$t_1 = t_0 - \frac{d}{2v_0}$$

$$t_2 = t_0 + \frac{d}{2v_0}$$

Equation (7) can be written as,

$$v(t) = v_0 - \frac{eV_1}{m\omega d}\left[\cos\omega\left(t_0 + \frac{d}{2v_0}\right) - \cos\omega\left(t_0 - \frac{d}{2v_0}\right)\right]$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{m\omega d}\left[2\sin\omega t_0 \sin\frac{\omega d}{2V_0}\right]$$

$$[\because \cos(A+B) - \cos(A-B) = -2\sin A \sin B].$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{mv_0}\frac{\sin\left[\frac{\omega d}{2v_0}\right]}{\left[\frac{\omega d}{2v_0}\right]}\sin\omega t_0$$

$$\Rightarrow \quad v(t) = v_0 + \frac{eV_1}{mv_0}\beta_i \sin\omega t_0$$

Where,

β_i – Beam coupling coefficient.

$$\beta_i = \frac{\sin\left(\frac{\omega d}{2v_0}\right)}{\frac{\omega d}{2v_0}}$$

$$\Rightarrow \quad v(t) = v_0\left[1 + \frac{eV_1}{mv_0^2}\beta_i \sin\omega t_0\right]$$

$$\Rightarrow \quad v(t) = v_0\left[1 + \frac{V_1}{2V_0}\beta_i \sin\omega t_0\right] \quad \left[\because v_0^2 = \frac{2eV_0}{m}\right]$$

$$\text{Excitation ratio, } \alpha = \frac{V_1}{V_0}$$

$$\boxed{\therefore v(t) = v_0\left[1 + \frac{\alpha\beta_i}{2}\sin\omega t_0\right]}$$

Q31. How the oscillations are generated in reflex klystron and explain bunching process with apple gate diagram and also derive the equation for efficiency. Dec.-19, (R16), Q6 M[10]

(or)

Derive the expression for bunching parameter of Reflex klystron. March-21, (R16), Q5(a)

(Refer Only Bunching Process)

Ans:

Operation

For answer refer Unit-1, Q30, Topic: Operation.

Bunching Process: Initially, the cavity-gap voltage velocity modulates the electron beam injected from the cathode. The accelerating field will accelerate the greater velocity electrons that enter into repeller space, than those with unchanged velocity. The retarding field decelerates low velocity electrons which then passed through the cavity gap in bunches. This process occurs once per cycle. During the retarding phase of the alternating field, the bunched electrons pass through the gap by giving up the kinetic energy to the electro magnetic energy of the field. Finally, the walls of the cavity collect the electrons. The applegate diagram for the reflex klystron is shown in figure.

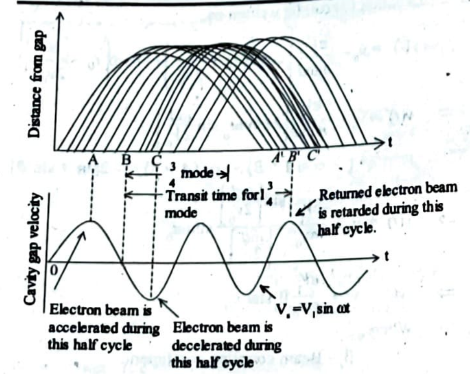


Figure: Applegate Diagram with Gap Voltage for a Reflex Klystron

The velocity with which electrons leave the cavity is given as,

$$v(t_1) = v_0\left[1 + \frac{\alpha\beta_i}{2}\sin\omega t_1\right] \quad \dots (1)$$

Where,

t_1 – Time at which electrons pass through the centre of the cavity.

Then, the force exerted in the electric field 'E' is given by,

$$F = ma = -eE \quad \dots (2)$$

$$\Rightarrow a = \frac{-e}{m}E$$

Assuming, the electrons are propagating in z-direction, then,

$$\frac{d^2z}{dt^2} = \frac{-e}{m}E_z \quad \left[\because a = \frac{d^2z}{dt^2}\right] \quad \dots (3)$$

The instantaneous gap voltage, V_g is given by,

$$V_g = V_1 \sin \omega t$$

$$\text{Field intensity, } E_z = \frac{V_g + V_0 - V_R}{L}$$

$$= \frac{(V_0 - V_R) + V_1 \sin\omega t}{L}$$

Since, $(V_0 - V_R) >> V_1 \sin \omega t$,

$$\Rightarrow E_z = \frac{(V_0 - V_R)}{L} \quad \dots (4)$$

Where,

L – Width of the cavity gap

Substituting 'E_z' value in equation (3),

$$\frac{d^2z}{dt^2} = \frac{-e}{m}\frac{(V_0 - V_R)}{L}$$

Integrating with respect to 't',

$$\frac{dz}{dt} = \int_{t_1}^{t} \frac{-e}{m}\frac{(V_0 - V_R)}{L}dt = \frac{-e}{m}\frac{(V_0 - V_R)}{L}[t]_{t_1}^{t} + C$$

$$\Rightarrow \frac{dz}{dt} = \frac{-e}{m}\frac{(V_0 - V_R)}{L}(t - t_1) + C$$

At $t = t_1$,

$$\frac{dz}{dt} = v(t_1)$$

$$\left.\frac{dz}{dt}\right|_{at\ t=t_1} = 0 + C$$

$$\Rightarrow C = v(t_1)$$

Hence,

$$\frac{dz}{dt} = \frac{-e}{m}\frac{(V_0 - V_R)}{L}(t - t_1) + v(t_1) \quad \dots (5)$$

Here, t_1 is the time at which electron pass through mid point or the gap for the first time. Assuming that t_2 is the time at which the electron returns to the gap from the repeller space. Hence, at $t = t_2$ equation (5) becomes,

$$\frac{dz}{dt} = \frac{-e}{m}\frac{(V_0 - V_R)}{L}(t_2 - t_1) + v(t_1)$$

$$v(t_2) = \frac{-e}{m}\frac{(V_0 - V_R)}{L}(t_2 - t_1) + v(t_1)$$

Here, $v(t_2) = -v(t_1)$

$$\Rightarrow -v(t_1) = \frac{-e}{m}\frac{(V_0 - V_R)}{L}(t_2 - t_1) + v(t_1) \quad [\because v(t_2) = -v(t_1)]$$

$$\Rightarrow 2v(t_1) = \frac{e}{m}\frac{(V_0 - V_R)}{L}(t_2 - t_1)$$

$$\Rightarrow t_2 - t_1 = \frac{2mLv(t_1)}{e(V_0 - V_R)}$$

From equation(2),

$$t_2 - t_1 = \frac{2mL}{e(V_0 - V_R)}v_0\left[1 + \frac{\alpha\beta_i}{2}\sin\omega t_1\right] \quad \dots (6)$$

Multiplying by 'ω' on both sides,

$$\omega t_2 - \omega t_1 = \frac{2\omega mL}{e(V_0 - V_R)}v_0\left[1 + \frac{\beta_i V_1}{2V_0}\sin\omega t_1\right]$$

$$\omega T = \omega T_0'\left[1 + \frac{\beta_i V_1}{2V_0}\sin\omega t_1\right] \quad [\because T = t_2 - t_1] \dots (7)$$

On comparing equation (7) with $\omega T = \theta_0' + X'\sin\omega t_1$,

$$\theta_0' = \omega T_0'$$

$$\theta_0' = \frac{2\omega mLV_0}{e(V_0 - V_R)} \text{ and } X' = \frac{2\omega mLV_0}{e(V_0 - V_R)} \cdot \frac{\beta_i V_1}{2V_0}$$

$$X' = \frac{\beta_i \alpha\theta_0'}{2} \quad \left[\because \alpha = \frac{V_1}{V_0}\right]$$

Here,

θ_0' – Round-trip D.C transit angle.

X – Bunching parameter of reflex klystron oscillator.

Q32. Formulate Power Output and Efficiency in Reflex Klystron amplifier.

Ans: Oct./Nov.-20, (R16), Q5(b)

Power Output of Reflex Klystron

In order to obtain the maximum power output of reflex klystron, a maximum amount of kinetic energy needs to be transferred from the returning electrons to the cavity walls. For a maximum energy transfer, the round-trip transmit angle is obtained as,

$$\theta_0' = \omega(t_2 - t_1) = \omega T_0'$$

$$= \left(n + \frac{3}{4}\right)2\pi$$

$$= 2n\pi + \frac{3\pi}{2} \quad \dots (1)$$

Where,

n – Positive integer including zero i.e., 0, 1, 2

$N = n + \frac{3}{4}$ – Number of modes

In a reflex klystron the current modulation of electron beam can be obtained in the same way as in the case of two cavity klystron. Thus, the beam current of a reflex klystron is expressed as,

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

From the above expression, the fundamental component of the induced curernt in the cavity with the help of modulated electron beam is obtained as,

$$i_2 = \beta_i I_2 = 2I_0\beta_i J_1(X')\cos(\omega t_2 - \theta_0') \quad \dots (3)$$

$$(\because \theta_0' >> \theta_g)$$

The magnitude of above expression can be written as,

$$I_2 = 2I_0\beta_i J_1(X') \quad \dots (4)$$

The dc or input power supplied by the beam voltage V_0 is given by,

$$P_{dc} = P_{in} = V_0 I_0 \quad \dots (5)$$

and the ac or output power delivered to the oad is obtained as,

$$P_{ac} = P_{out} = \frac{V_1 I_2}{2}$$

$$P_{out} = V_1 I_0 \beta_i J_1(X') \quad \dots (6)$$

From the expresson of bunching parameter is,

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

$$\Rightarrow V_1 = \frac{2V_0 X'}{\theta_0'\beta_i} \quad \dots (7)$$

Substituting 'V_1' value in expression (6), we get,

$$P_{out} = \frac{2V_0 X'}{\beta_i\theta_0'} I_0\beta_i J_1(X')$$

$$= \frac{2V_0 I_0 X' J_1(X')}{\theta_0'} = \frac{2V_0 I_0 X' J_1(X')}{2n\pi + \frac{3\pi}{2}}$$

$$\boxed{\therefore P_{out} = \frac{2V_0 I_0 X J_1(X')}{2n\pi + \frac{3\pi}{2}}}$$

Efficiency of Reflex Klystron

The effeciency of the reflex klystron is given by the ratio of P_{ac} to P_{dc}.

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{P_{out}}{P_{in}} \quad \dots (8)$$

The input and output powers of the reflex klystron are given by,

$$P_{in} = V_0 I_0$$

$$\text{and } P_{out} = \frac{2V_0 I_0 X' J_1(X')}{2n\pi + \frac{3\pi}{2}}$$

From equation (10),

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\frac{2V_0 I_0 X' J_1(X')}{2n\pi + \frac{3\pi}{2}}}{V_0 I_0}$$

$$= J_1(X')\frac{V_1}{V_0} = \frac{2X' J_1(X')}{\theta_0'}$$

$$\eta = \frac{2X' J_1(X')}{2\pi(n + 3/4)}$$

The maximum efficiency is obtained for $n = 1$ and maximum of $X'J_1(X')$ is 1.252 for $X' = 2.408$.

$$\eta_{max} = \frac{1.252}{\pi(1 + 3/4)} = 0.2278$$

$$\therefore \boxed{\eta_{max} = 22.78\%}$$

Q33. Derive the expressions for repeller voltage and electronic efficiency of reflex krystron.

Ans:

The electrons injected into the tube travel with an initial velocity, v_0 and V_0 is the dc voltage applied across the tube. Then, the energy of the electron is equal to the kinetic energy gained by the electrons i.e.,

$$\frac{1}{2}mv_0^2 = eV_0$$

$$\Rightarrow V_0 = \frac{m}{2e}.v_0^2 \quad \dots (1)$$

The transit angle, θ'_0 is defined as,

$$\theta'_0 = \frac{-2mL\omega v_0}{e(V_R - V_0)} \quad ...(2)$$

Where,

$\frac{e}{m}$ – Electron charge mass ratio

L – Distance between cavity gap and repeller electrode

ω – Frequency of operation in radians per second

v_0 – Velocity of electron

V_R – Repeller voltage.

$$\Rightarrow \quad v_0 = \frac{-\theta'_0 e(V_R - V_0)}{2mL\omega}$$

Substituting 'v_0' value in equation (1),

$$V_0 = \frac{m}{2e}\left[\frac{\theta'_0 e(V_R - V_0)}{2mL\omega}\right]^2$$

$$V_0 = \frac{e}{m} \times \frac{1}{8}(\theta'_0)^2 \frac{(V_R - V_0)^2}{L^2\omega^2}$$

$$\frac{8mV_0L^2\omega^2}{e(\theta'_0)^2} = (V_R - V_0)^2$$

$$V_R - V_0 = \sqrt{\frac{8mV_0L^2\omega^2}{e(\theta'_0)^2}}$$

$$V_R = V_0 + \sqrt{\frac{8mV_0L^2\omega^2}{e(\theta'_0)^2}}$$

$$\Rightarrow \quad V_R = V_0 + 2\sqrt{2V_0\left(\frac{m}{e}\right)}\frac{L\omega}{\theta'_0}$$

$$\Rightarrow \quad V_R = V_0 + \frac{2\omega L}{\theta'_0}\sqrt{2V_0\left(\frac{m}{e}\right)}$$

Substituting, $\frac{e}{m} = 1.759 \times 10^{11}$ C/kg in above equation,

$$\boxed{\therefore V_R = V_0 + \frac{(6.74\times10^{-6})\omega L}{\theta'_0}\sqrt{V_0}}$$

Q34. Derive the expression for transadmittance of reflex klystron oscillator and explain the condition of oscillation from admittance spiral.

Ans:

Figure (1) shows the equivalent circuit of a reflex klystron oscillator,

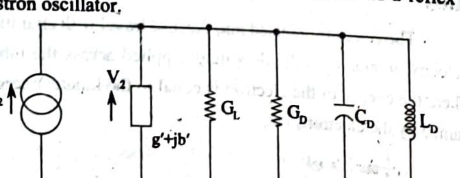


Figure (1)

The output current, I_2 of the reflex klystron in the phasor form is given by,

$$I_2 = 2I_0 J_1(X').e^{-j\theta'_0} \quad ...(1)$$

The output voltage, V_2 of the reflex klystron in the phasor form is given by,

$$V_2 = V_1 e^{-j\pi/2} \quad ...(2)$$

Then, the transadmittance or electronic admittance is given by,

$$Y_e = \frac{I_2}{V_2}$$

From equations (1) and (2),

$$Y_e = \frac{2I_0J_1(X')e^{-j\theta'_0}}{V_1e^{-j\pi/2}} \quad ...(3)$$

Where,

I_0 – D.C current

$J_1(X')$ – First order bessel function

V_1 – Amplitude of the input RF signal.

But, the amplitude of the input RF signal of the reflex klystron is given by,

$$V_1 = \frac{2V_0X'}{\beta_i\theta'_0}$$

Substituting 'V_1' value in equation (3),

$$Y_e = \frac{2I_0J_1(X')e^{-j\theta'_0}}{\frac{2V_0X'}{\beta_i\theta'_0}e^{-j\pi/2}}$$

$$\boxed{Y_e = \frac{I_0\beta_i\theta'_0J_1(X')}{V_0X'}e^{j\left(\frac{\pi}{2}-\theta'_0\right)}} \quad ...(4)$$

When the net admittance is less than zero, oscillations are produced in the reflex klystron.

As, $Y_e = G_e + jB_e$

Then, the condition for oscillation is,

$$\boxed{|-G_e| \geq G}$$

$$G = \frac{1}{R_{sh}} = G_0 + G_L + G_b$$

Where,

R_{sh} – Shunt resistance

G_0 – Copper cavity losses

G_L – Load conductance

G_b – Beam load conductance $= g' + jb'$

Figure (2) shows a rectangular plot of $G_e + jB_e$ which will be a spiral. The transadmittance, Y_e is a function of transit angle θ'_0.

For $n = 0$, $\theta'_0 = 2n\pi - \frac{\pi}{2} = -\frac{\pi}{2}$

$n' = 1$, $\theta'_0 = \frac{3\pi}{2}$

$n = 2$, $\theta'_0 = \frac{7\pi}{2}$

$n = 3$, $\theta'_0 = \frac{11\pi}{2}$

$n = 4$, $\theta'_0 = \frac{15\pi}{2}$

Upto $n = 7$, the oscillations are possible in reflex klystron practically. The corresponding electronic admittance spiral of a reflex klystron is shown in figure (2).

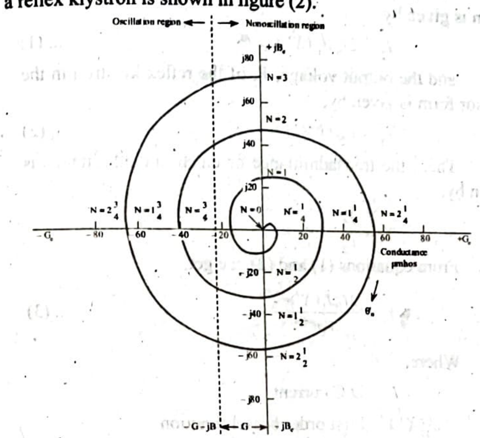


Figure (2): Electronic Admittance Spiral of a Reflex Klystron

Q35. Explain the performance characteristics of a reflex klystron tube with neat sketch.

Ans:

The performance of a reflex klystron depends on two types of characteristics. They are,

1. **Voltage Characteristics**

The required specific combinations of anode and repeller voltages are used to produce the oscillations and that will give a favourable transit time i.e., $T = \left(n + \frac{3}{4}\right)$.

The possible oscillation combinations and optimum combinations are shown by shaded areas and heavy lines respectively in figure (1). For different values of 'n' i.e., $n = 1, 2, 3, ...$ the reflex klystron oscillator is operated in different modes. The mode with larger output power is not advantageous but it should have higher voltages as shown in figure (1). This leads to the possibilities of lower efficiencies and insulation problems. Hence, modes corresponding to $n = 2$ or $n = 3$ are most widely used.

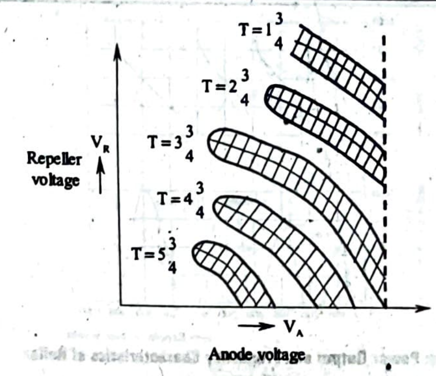


Figure (1): Voltage Characteristics of Reflex Klystron

2. **Power Output and Frequency Characteristics**

Figure (2) shows the frequency characteristics of the mode curves. The frequency of oscillation is decided by the frequency of resonance of the cavity. This frequency is slightly changed by the variations in repeller voltage. This will describe the electronic tuning of reflex klystron and is also illustrated in figure (2). Thus, the reflex klystron can be used as,

1. Voltage tuned oscillator
2. Frequency modulated oscillator.

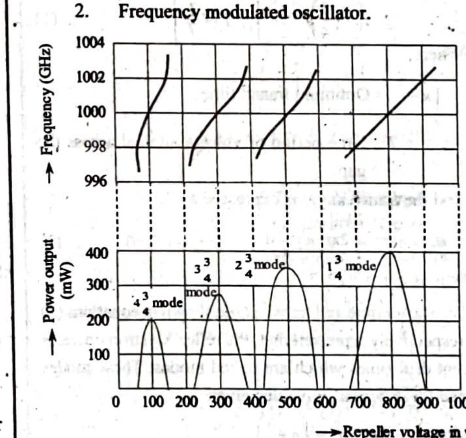


Figure (2): Power Output and Frequency Characteristics of Reflex Klystron

Q36. Draw the mode curves of reflex klystron and derive the relation between mode number and repeller in reflex klystron.

Ans: (Model Paper, Q3(a) | Nov./Dec.-17, (R13), Q6(a))

Mode Curves of Reflex Klystron

The curves which describe the variations in power output and frequency with changes in the repeller voltage are called mode curves, which are shown in figure.

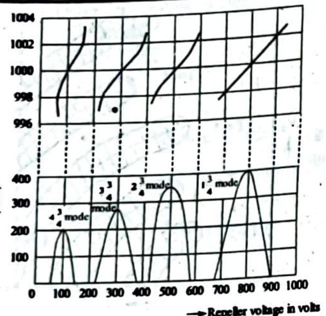


Figure: Power Output and Frequency Characteristics of Reflex Klystron

Relation between Mode Number and Repeller

In a reflex klystron, the electron bunch formed at the repeller must reach the cavity resonator at the transit time, so that the electrons bunch is severely decelerated. In the process of deceleration, the electrons give up their energy, which is used to reinforce the oscillations in the cavity.

This transit time is expressed as,

$$T_0' = \frac{n+3/4}{f}$$

$$T_0' = \left(n+\frac{3}{4}\right)T \quad \left[\because T=\frac{1}{f}\right] \quad \ldots (1)$$

Where,

$\left(n+\frac{3}{4}\right)$ - Optimum transit time

T - Time period of voltage applied across the gap.

And the transit angle is expressed as,

$$\theta_0' = \omega T_0' = 2\pi f\left(n+\frac{3}{4}\right)T \quad [\because \omega = 2\pi f] \quad \ldots (2)$$

Where, $n = 0, 1, 2, 3, \ldots$

The transit time and transit angle shown in equations (1) and (2) respectively represent that, the reflex klystron operates at different drift times which are called modes. These modes are defined for different 'n' values given as,

Mode number, $N_n = \left(n+\frac{3}{4}\right)$

Where,

$n = 0$ is called $\frac{3}{4}$ mode

$n = 1$ is called $1\frac{3}{4}$ mode etc.

When the anode voltage (V_0) and resonant frequencies are fixed, the mode number and repeller are related as,

$$\frac{(|V_{R_1}|+V_0)}{(|V_{R_2}|+V_0)} = \frac{N_2}{N_1}$$

Where, $|V_{R_1}|$ and $|V_{R_2}|$ are the repeller voltages that are used to operate the Klystron in mode numbers N_1 and N_2 respectively.

Q37. Derive the expression for transadmittance of reflex klystron oscillator and explain the condition of oscillation from admittance spiral.

Ans:

Transadmittance of Reflex Klystron Oscillator: Figure (1) shows the equivalent circuit of a reflex klystron oscillator.

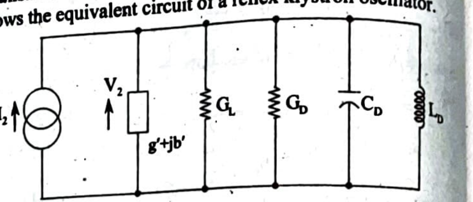


Figure (1)

The output current, I_2 of the reflex klystron in the phasor form is given by,

$$I_2 = 2I_0 J_1(X').e^{-j\theta_0} \quad \ldots (1)$$

and the output voltage, V_2 of the reflex klystron in the phasor form is given by,

$$V_2 = V_1 e^{-j\pi/2} \quad \ldots (2)$$

Then, the transadmittance or electronic admittance is given by,

$$Y_e = \frac{I_2}{V_2}$$

From equations (1) and (2), we get,

$$Y_e = \frac{2I_0 J_1(X')e^{-j\theta_0}}{V_1 e^{-j\pi/2}} \quad \ldots (3)$$

Where,

I_0 = D.C current

$J_1(X')$ = First order bessel function

V_1 = Amplitude of the input RF signal.

But, the amplitude of the input RF signal of the reflex klystron is given by,

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

Substituting 'V_1' value in equation (3), we get,

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

$$\boxed{Y_e = \frac{I_0\beta_i\theta_0' J_1(X')}{V_0 X'} e^{j\left(\frac{\pi}{2}-\theta_0\right)}} \quad \ldots (4)$$

When the net admittance is less than zero, oscillations are produced in the reflex klystron.

As, $Y_e = G_e + jB_e$

Then, the condition for oscillation is,

$$\boxed{|-G_e| \geq G}$$

$$G = \frac{1}{R_{sh}} = G_0 + G_L + G_b$$

Where,

R_{sh} = Shunt resistance

G_0 = Copper cavity losses

G_L = Load conductance

G_b = Beam load conductance $= g' + jb'$

Figure (2) shows a rectangular plot of $G_e + jB_e$ which will be a spiral. The transadmittance, Y_e is a function of transit angle θ_0'.

For $n = 0$, $\theta_0' = 2n\pi - \frac{\pi}{2} = -\frac{\pi}{2}$

$n = 1$, $\theta_0' = \frac{3\pi}{2}$

$n = 2$, $\theta_0' = \frac{7\pi}{2}$

$n = 3$, $\theta_0' = \frac{11\pi}{2}$

$n = 4$, $\theta_0' = \frac{15\pi}{2}$

Upto $n = 7$, the oscillations are possible in reflex klystron practically. The corresponding electronic admittance spiral of a reflex klystron is known in figure (2).

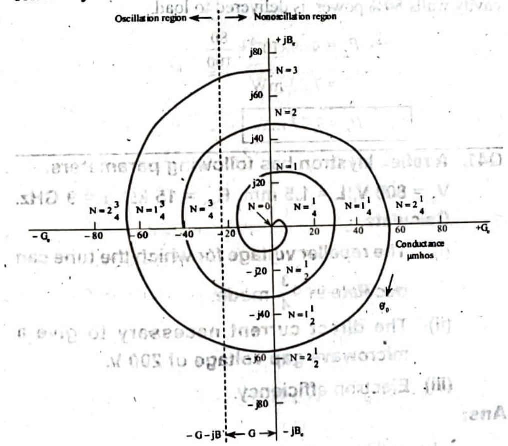


Figure (2): Electronic Admittance Spiral of a Reflex Klystron

Q38. Explain about electronic and mechanical tuning in reflex klystron.

Nov./Dec.-18, (R13), Q6(a)

Ans:

Electronic Tuning

Electronic tuning is possible by adjusting of the repeller voltage (V_R). The tuning range is about ± 8 MHz at X-band and ± 80 MHz for submillimeter klystron.

$$\text{Since, } (V_R + V_0)^2 = \frac{8ms^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 e}\omega^2 \quad \ldots (1)$$

Differentiating 'V_R' with respect to ω,

$$2(V_R + V_0)\frac{dV_R}{d\omega} = \frac{16ms^2 V_0}{\left(2\pi n - \frac{\pi}{2}\right)^2 e}\omega$$

$$\Rightarrow \frac{dV_R}{d\omega} = \frac{8ms^2 V_0}{e\left(2\pi n - \frac{\pi}{2}\right)}\frac{\omega}{(V_R + V_0)} \quad \ldots (2)$$

Substituting the value of $V_R + V_0$ from equation (1),

$$V_R + V_0 = \sqrt{\frac{8ms^2 V_0 \omega^2}{e\left(2\pi n - \frac{\pi}{2}\right)^2}} \quad \ldots (3)$$

From equation (2) and (3), we get,

$$\frac{dV_R}{d\omega} = \frac{8ms^2 \omega V_0}{e\left(2\pi n - \frac{\pi}{2}\right)^2} \times \sqrt{\frac{e\left(2\pi n - \frac{\pi}{2}\right)^2}{8ms^2 V_0 \omega^2}}$$

$$= \sqrt{\frac{8ms^2 V_0}{e} \cdot \frac{1}{\left(2\pi n - \frac{\pi}{2}\right)^2}}$$

$$\frac{dV_R}{df} = \frac{2\pi s}{\left(2\pi n - \frac{\pi}{2}\right)}\sqrt{\frac{8mV_0}{e}}$$

If repeller voltage is varied by even 2%, frequency changes considerably.

As the variation in frequency is quite sensitive to repeller voltage adjustments, it draws large current and get overheated.

The precaution to be taken that the of repeller voltage need to be applied prior to application of anode voltage and connection of a protective diode across the klystron, so that repeller can never become positive.

Mechanical Tuning

Mechanical tuning of reflex klystron may range from ± 20 MHz at X-band to ± 4 GHz at 200 GHz frequency.

The frequency of resonance is mechanically adjusted using tunable screws or posts. When a screw or sliding piston is used to tune cavity piston, the Q decreases due to the presence of current flowing through tuning elements. The resonant frequency gets affected by the dielectric materials.

In the other method, consists of a wall is used to adjusted and fro by means of a screw, which tightens or loosens small bellows. This method can be used with permanent cavities, which are built into reflex klystrons (as a form of limited frequency shifting). Hence, there is a possibility of changing the resonant frequency through mechanical tuning.

Q39. Design the input voltage and electronic efficiency when the beam voltage V_0 = 250 V, beam current I_g = 10 mA, and the signal voltage V_{ss} = 25 V are the parameters of a reflex klystron which operates at the mode n = 2.

Oct./Nov.-20, (R16), Q6(b)

Ans:

Given that,

For a reflex klystron,

Beam voltage, $V_0 = 250$ V

Beam current, $I_g = 10$ mA

Signal voltage, $V_{ss} = 25$ V

Operating mmode, $n = 2$

Input voltage, V_i = ?

Electronic efficiency, η = ?

Then, the input voltage V_i of a reflex klystron can be obtained as,

$$V_i = \frac{2V_0X'}{\beta_i\theta_0}$$

Inorder to obtain maximum 'V_i', $J_1(X')$ must be maximum. This means $J_1(X') = 0.582$ for $X' = 1.841$. Then,

$$V_i = \frac{2V_0X'}{\left(n+\frac{3}{4}\right)2\pi} \quad [\because \beta_i = 1]$$

$$= \frac{2\times250\times1.841}{\left(2+\frac{3}{4}\right)2\pi}$$

$$= \frac{2\times250\times1.841\times7\times4}{11\times2\times22}$$

$$= 53.25 \text{ V}$$

$$\boxed{\therefore V_i = 53.25 \text{ V}}$$

and the electronic efficiency of a reflex klystron is obtained as,

$$\eta = \frac{2X'J_1(X')}{2\pi\left(n+\frac{3}{4}\right)}$$

$$= \frac{2\times1.841\times0.582}{2\pi\left(2+\frac{3}{4}\right)}$$

$$= \frac{1.841\times0.582\times7\times4}{22\times11}$$

$$= 0.124 = 12.4\%$$

$$\boxed{\therefore \eta = 12.4\%}$$

Q40. A reflex klystron operates at the peak of the n = 2 mode. The dc power input is 40 mW and the ratio of V_1 over V_0 is 0.278. If 20% of power delivered by the beam is dissipated in the cavity walls, find the power delivered to the load. (V_1 = Signal voltage and V_0 = Beam voltage).

Ans:

Given that,

For a reflex klystron,

Oscillating mode, $n = 2$

D.C power input, $P_{in} = 40$ mW

Ratio, $\frac{V_1}{V_0} = 0.278$

With 20% power dissipated in the cavity power delivered to load P_L = ?

The expresion for input power is given by,

$$P_{in} = V_0I_0 = 40 \text{ mW}$$

The output power of reflex klystron is given by,

$$P_{out} = \frac{2V_0I_0\times J_1(X')}{2n\pi-\frac{\pi}{2}} = \frac{2P_{in}\,J_1(X')}{2n\pi-\frac{\pi}{2}}$$

$$= \frac{2\times40\times10^{-3}\times1.25}{2\times2\times\pi-\frac{\pi}{2}}$$

$$P_{out} = 9.09 \text{ mW}$$

As 20% of the power delivered by beam is dissipated in cavity walls 80% power is delivered to load,

$$\Rightarrow P_L = 9.09\times10^{-3}\times\frac{80}{100}$$

$$= 7.27 \text{ mW}$$

$$\boxed{\therefore P_L = 7.27 \text{ mW}}$$

Q41. A reflex klystron has following parameters. V_0 = 800 V, L = 1.5 mm. R_{sh} = 15 kΩ, f = 9 GHz. Calculate,

(i) The repeller voltage for which the tube can oscillate in $1\frac{3}{4}$ mode.

(ii) The direct current necessary to give a microwave gap voltage of 200 V.

(iii) Electron efficiency.

Ans:

Given that,

For a reflex klystron,

$V_0 = 800$ V

$L = 1.5$ mm

$R_{sh} = 15$ kΩ

$f = 9$ GHz

(i) For the tube to oscillate in $n = 1\frac{3}{4}$ used repeller voltage, V_R = ?

(ii) For producing a microwave gap voltage $V_1 = 200$ V, required direct current, I_0.

(iii) Electrons efficiency, μ = ?

(i) For the tube to oscillate in $n = 1\frac{3}{4}$ mode, the repeller voltage is obtained as,

$$\text{Since, } \frac{V_0}{(V_R+V_0)^2} = \frac{1}{8}\cdot\frac{1}{\omega^2L^2}\cdot\frac{e}{m}\left[2\pi n-\frac{\pi}{2}\right]^2$$

$$= \frac{1}{8}\times\frac{(1.759\times10^{11})\left(2\pi\times2-\frac{\pi}{2}\right)^2}{(2\pi\times9\times10^9)^2(1.5\times10^{-3})^2}$$

$$= \frac{1}{8}\times\frac{2.13\times10^{13}}{7.19\times10^{15}} = 0.00037$$

$$\frac{V_0}{(V_R+V_0)^2} = 0.00037$$

$$(V_R+V_0)^2 = \frac{800}{0.00037} = 2162162$$

$$V_R + V_0 = 1470$$

$$V_R = 1470 - 800$$

$$V_R = 670 \text{ V}$$

$$\boxed{\therefore \text{Repeller voltage, } V_R = 670 \text{ V}}$$

(ii) For producing a microwave gap volage, $V_1 = 200$ V, the required dc current is obtained as,

Then, $V_1 = R_{sh}I_2 \quad [\because \beta_0 = 1]$

$$= 2I_0J_1(X')R_{sh}$$

$$I_0 = \frac{V_1}{2J_1(X')R_{sh}}$$

$$I_0 = \frac{200}{2\times0.582\times15\times10^3} = 11.45\times10^{-3}$$

$$\therefore I_0 = 11.45 \text{ mA}$$

(iii) The expression for efficiency of a reflex klystron is given by,

$$\eta = \frac{2X'J_1(X')}{2\pi n-\frac{\pi}{2}} \quad \text{... (1)}$$

Where, $X' = \frac{\beta_iV_1\theta_0'}{2V_0}$

$$\Rightarrow \theta_0' = \omega T_0' = \frac{\omega2\times mLV_0}{e(V_R+V_0)}$$

$$= \frac{2\pi\times9\times10^9\times2\times1.5\times10^{-3}\times0.593\times10^6\sqrt{800}}{1.759\times10^{11}\times(670+800)}$$

$$= \frac{2.84\times10^{15}}{2.586\times10^{14}}$$

$$\Rightarrow \theta_0' = 10.982$$

$$\text{Then, } X' = \frac{1\times200\times10.982}{2\times800}$$

$$X' = 1.373$$

On substituting corresponding values in equation (1), we get,

$$\eta = \frac{2\times1.373\times0.582}{4\pi-\frac{\pi}{2}}$$

$$\eta = 0.1453$$

$$\eta = 14.53\%$$

Q42. The operating frequency of a reflex klystron is 5 GHz, it has a DC beam of 250 V, a repeller spacing of 0.1 cm for $1\frac{3}{4}$ mode. Determine the maximum value of power and the corresponding repeller voltage for a beam current of 60 mA.

Nov.-13, (R09), Q5(b)

Ans:

Given that,

For a reflex klystron,

Operating frequency, $f = 5$ GHz

DC beam voltage, $V_0 = 250$ V

Repeller space, $L = 0.1$ cm

Mode, $N = 1\frac{3}{4}$

Beam current, $I_0 = 60$ mA

Maximum power, P_{max} = ?

Repeller voltage, V_R = ?

Then, the expression to calculate the maximum power in the cavity is given by,

$$P_{max} = \frac{0.398V_0I_0}{N}$$

$$= \frac{0.398\times250\times60\times10^{-3}}{1\frac{3}{4}}$$

$$= \frac{4\times0.398\times250\times60\times10^{-3}}{7}$$

$$= \frac{23.88}{7}$$

$$= 3.411 \text{ Watts}$$

$$\boxed{\therefore P_{max} = 3.411 \text{ Watts}}$$

The expression for repeller voltage of a reflex klystron is given by,

$$|V_R| = \left[6.75\times10^{-6}f_{(HZ)}L_{(m)}\frac{\sqrt{V_0}}{N}\right] - V_0$$

Here,

$$L_m = 0.1\times10^{-2} \text{ m}$$

$$= 10^{-3} \text{ m}$$

$$N = 1\frac{3}{4}$$

$$= 1.75$$

$$|V_R| = \left[6.74\times10^{-6}\times5\times10^9\times10^{-3}\times\frac{\sqrt{250}}{1.75}\right] - 250$$

$$= 304.48 - 250$$

$$|V_R| = 54.48$$

$$\boxed{\therefore V_R = -54.48 \text{ Volts}}$$

1.2 Helix TWTs

1.2.1 Types and Characteristics of Slow-wave Structures

Q43. Discuss the significance and types of Helix TWTs.

(or)

Explain in detail about slow-wave structures.

Oct./Nov.-20, (R16), Q6(a)

Ans:

Slow-wave Structures

The circuits that are used to decrease the wave velocity in a particular direction to meet the electron beam with input RF signal wave are known as slow-wave structures.

In microwave tubes, the frequency of resonance is maintained by reducing the inductance and capacitance while increasing the operating frequency of resonator. Furthermore, the resonator circuit is not suitable for producing the large output power and it has limited gain-bandwidth product. Thus, in order to generate large gain over a wide bandwidth, non resonant periodic or slow-wave structures are used in microwave tubes.

The most commonly used slow wave structures in microwave tubes are as shown in figure.

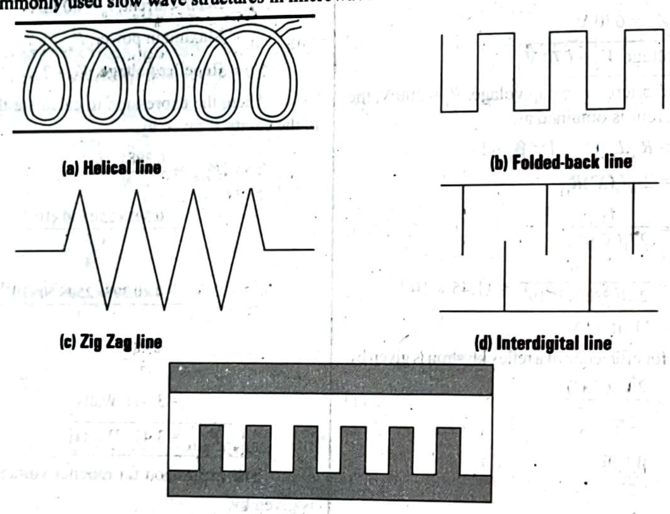


Figure: Slowwave Structure

Slow-wave Structures are introduced into the microwave devices to change the phase velocity of a microwave signal in accordance with electron beam for effective communication. The helical line structures with a concentric conducting cylinders are frequently used in microwave tubes.

Significance

In travelling wave tube(TWT), the electrons in the tube travel with a constant velocity i.e., velocity of light. Hence, no electron accelerates faster than the travelling wave on wire. Thus, the formation of bulk cluster(bunching) in TWTs is eliminated.

This drawback can be overcome by using slow wave structures. These allows the bunching process by reducing the speed of travelling waves below the electron beam speed. This setup also produces large gain over a wide band width.

Q44. What is a slow wave structure? List the different slow wave structures. Mention their relative merits and demerits.

Nov./Dec.-12, (R09), Q6(b)

Ans:

Slow-wave Structure

For answer refer Unit-1, Q43.

Merits and Demerits of Different Slow-wave Structures

1. **Helical-Line**

Merits

(i) Helix structure provides sufficient bandwidth required for broadband travelling wave tubes.

(ii) It features good chromatic dispersion.

(iii) The fluctuations of its output parameters in broadband range are very small.

(iv) Helical-wave system provides wideband characteristics.

(v) Suitable for low temperature experiments.

Demerits

(i) Low energy and power handling capability.

(ii) Efficiency is less.

(iii) Gain is reduced by the internal attenuator.

(iv) It suffers from manufacturing problems at high frequencies.

(v) Sufficient amount of heat dissipation is not provided.

2. **Folded-Back Line**

Merits

(i) Folded-back transmission line is suitable in designing Backward Wave Oscillators (BWO)

(ii) It supports the characteristics of helix structure.

Demerit

(i) Bandwidth is limited.

3. **Zig-zag Line**

Merits

(i) This structure forms inductive part of slow wave structure which provides synchronization with electron beam.

(ii) It performs shaping of dispersion characteristics.

(iii) Insertion loss is reduced.

Demerits

(i) Weight is more at very high frequencies.

(ii) Cost is more.

4. **Interdigital Line**

Merits

(i) The dispersion is negative, due to which design of amplifier and BWO (Backward Wave Oscillator) is made easy.

(ii) Heat dissipation is good.

Demerits

(i) Requires high temperature for operation.

(ii) The structure suffers from fabrication problems.

5. **Corrugated Waveguide**

Merits

(i) Coupling efficiency is high.

(ii) It is suitable for high frequency applications.

(iii) Propagation loss is very less.

Demerits

(i) Narrow bandwidth is provided.

(ii) Weight is more.

(iii) It has high cross polarization.

(iv) Various difficulties are encountered at the time of manufacture.

1.2.2 Structure of TWT and Amplification Process (Qualitative Treatment), Suppression of Oscillations, Gain Considerations

Q45. What is the significance of slow wave structure? Explain the amplification process in TWT.

March-21, (R16), Q5(b)

(or)

Explain how a helical TWT achieve amplification.

Nov./Dec.-18, (R13), Q7(a)

(or)

Explain how amplification takes place in Helix TWT?

(Refer Only Working)

Nov./Dec.-17, (R13), Q7(b)

(or)

With a neat sketch explain the structure and principle of operation of TWT amplifier.

(Refer Only Working)

Nov./Dec.-17, (R13), Q9(a)

(or)

Explain the principle of working of travelling wave tube.

(Refer Only Working)

Nov./Dec.-16, (R13), Q7(b)

Ans:

Significance of Slow-wave Structure

For answer refer Unit-1, Q43, Topic: Significacne.

Travelling Wave Tube

Travelling wave tube is a wide bandwidth or broadband microwave amplifier or voltage amplifier which is designed to provide high gain and low noise when used in a microwave equipment.

Construction

The construction of a helix travelling wave tube is as shown in figure (1).

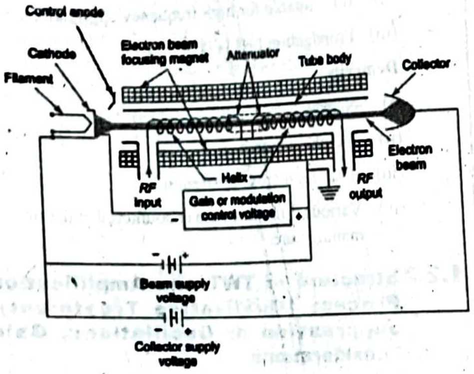


Figure (1): Travelling Wave Tube

In figure (1), the TWT consists of an electron gun, which when gets heated to generate electron beam that accelerates along the tube axis. Two magnets surrounding the tube provides magnetic field to focus the electrons into a narrow beam.

TWT is a non-resonant type microwave tube. Since, a slow wave structure(helical coil) is arranged along the axis of the tube. The input signal travels along the helical path and generates electric field at the center. TWT is designed in such a way that the speed/velocity of the travelling wave is maintained closer to speed of electron beam multiplied by the ratio of pitch of helix to helix circumference. The electron beam injected into the tube interacts with input signal wave. The bunching occurs in the tube due to the velocity modulation which further traverse the electron energy to travelling wave.

Working: When a RF signal wave is injected into the helix slow wave guide, it travels in the form of axial *E*-field. As the signal travels through helix, the electron bunches release energy which result in amplification.

The denser bunch of electrons amplifies the signal until the RF wave and electron beam travel down the tube length. This energy of the bunch compensates the loss in system and provides constant amplification of signal at the output.

The reflected waves produced due to impedance mismatch are attenuated by the attenuator, placed at the centre of interaction region.

The interaction between accelerating field, electron beam and retarding field is as shown in figure (2).

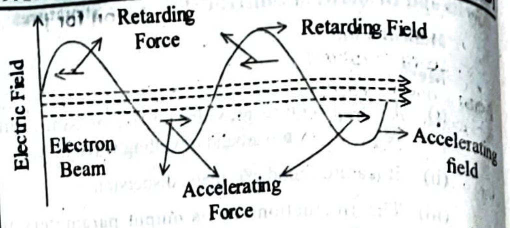


Figure (2): Interaction between Electron Beam and Electric Field

The time taken by the signal to travel along the wire is given by,

$$T = \frac{P}{V_p} = \sqrt{\frac{p^2 + (\pi d)^2}{C}}$$

Where,

p – Helix pitch

d – Helix diameter

$$\Rightarrow V_p = \frac{Cp}{p^2 + (\pi d)^2} \approx \frac{Cp}{\pi d} \approx \frac{\omega}{\beta}, \; p << \pi d$$

The electrons gets accelerated when the electron field is applied against the electron flow and when applied along the electron flow, decelerates the electron. This density modulation results in electron bunch formation.

Since, the electrons experience more retarding field than accelerating field, the bunch formation increases with increase in field amplitude. This results in large amplification of signal voltage at helix output.

Q46. Explain with neat sketch, the principle of operation of a TWT amplifier and write the equations for the maximum voltage gain and efficiency.

Ans: April/May-18, (R13), Q7(b)

TWT Amplifier

For answer refer Unit-1, Q45.

Gain and Efficiency Equations

The expression for power gain (in dB) of a TWT is given by,

$$A_p = -9.54 + 47.3 \, NC \text{ dB}$$

Where,

N – Length of slow wave structure (in m)

C – Gain parameter $= \left(\frac{I_0 Z_0}{4V_0}\right)^{1/3}$

V_o – dc beam voltage

I_o – dc beam current

Z_o – Characteristics impedance of the helix.

The efficiency of TWT is in the range of 20% to 40%.

Q47. Establish the mathematical relation for power gain in a TWT amplifier, and explain the parameters involved.

Ans: Consider a perfectly matched structure with an attenuator is placed at the centre of the tube.

The overall voltage is the sum of individual voltages of forward travelling waves.

$$V(z) = V_1 e^{-\gamma_1 z} + V_2 e^{-\gamma_2 z} + V_3 e^{-\gamma_3 z}$$

$$= \sum_{n=1}^{3} V_n e^{-\gamma_n z} \quad \text{... (1)}$$

Then, the total input current is given by,

$$i(z) = -\frac{I_0}{2V_0C^2} \cdot \frac{V_1 e^{-\gamma_1 z}}{\delta_1^2} - \frac{I_0}{2V_0C^2} \cdot \frac{V_2 e^{-\gamma_2 z}}{\delta_2^2} - \frac{I_0}{2V_0C^2} \cdot \frac{V_3 e^{-\gamma_3 z}}{\delta_3^2}$$

$$\Rightarrow \quad i(z) = -\sum_{n=1}^{3} \frac{I_0}{2V_0C^2} \cdot \frac{V_n e^{-\gamma_n z}}{\delta_n^2} \quad \text{... (2)}$$

Where,

V_o, I_o – Beam voltage and current

γ_1 – Forward wave whose amplitude grows exponentially with distance.

γ_2 – Forward wave whose amplitude decays exponentially with distance.

γ_3 – Forward wave whose amplitude remains constant.

C – Gain parameter.

$$C = \left[\frac{I_o Z_o}{4V_o}\right]^{1/3}$$

$$\delta = (-j)^{1/3}$$

since, $C\delta << 1, E_1 = \gamma V, \gamma = j\beta_e(1 - C\delta)$, the total wave velocity is given by,

$$v_1(z) = \frac{j v_0}{2V_0C} \cdot \frac{V_1 e^{-\gamma_1 z}}{\delta_1} + \frac{j v_0}{2V_0C} \cdot \frac{V_2 e^{-\gamma_2 z}}{\delta_2} + \frac{j v_0}{2V_0C} \cdot \frac{V_3 e^{-\gamma_3 z}}{\delta_3}$$

$$= \sum_{n=1}^{3} \frac{j v_0}{2V_0C} \cdot \frac{V_n}{\delta_n} e^{-\gamma_n z} \quad \text{... (3)}$$

Where,

$$v_o = \sqrt{\left(\frac{2e}{m}\right)V_0}$$

$$\beta_e = \frac{\omega}{v_0}$$

At the input reference point i.e., $z = 0$

$$V(0) = V_1 + V_2 + V_3 \quad \text{... (4)}$$

$$i(0) = -\frac{I_0}{2V_0C^2}\left[\frac{V_1}{\delta_1^2} + \frac{V_2}{\delta_2^2} + \frac{V_3}{\delta_3^2}\right] \quad \text{... (5)}$$

($\because$ From equation (2))

$$v_1(0) = \frac{j v_0}{2V_0C}\left[\frac{V_1}{\delta_1} + \frac{V_2}{\delta_2} + \frac{V_3}{\delta_3}\right] \quad \text{... (6)}$$

($\because$ From equation (3))

By simultaneously solving above equations (4), (5) and (6) for $i(0) = 0$ and $v_1(0) = 0$, the solution obtained is,

$$\boxed{V_1 = V_2 = V_3 = \frac{V(0)}{3}} \quad \text{... (7)}$$

As the wave increases exponentially (with distance) above the total voltage along the circuit, the output voltage becomes equal to the voltage of the growing wave for sufficiently large value of 'l'.

$$\text{For} \quad z = l, \gamma_1 = -\beta_e C \frac{\sqrt{3}}{2} + j\beta_e\left(1 + \frac{C}{2}\right) \quad \text{... (8)}$$

At the output reference i.e., $z = l$, $V(l)$ can be obtained by substituting equations (7) and (8) in equation (1) as,

$$V(l) = \frac{V(0)}{3} \exp\left[-\left[\beta_e C \frac{\sqrt{3}}{2} + j\beta_e\left(1 + \frac{C}{2}\right)\right]l\right]$$

$$= \frac{V(0)}{3} \exp\left[\frac{\sqrt{3}}{2}\beta_e Cl\right] \exp\left[-j\beta_e\left(1 + \frac{C}{2}\right)l\right]$$

Here, $N = \frac{l}{\lambda_e}$ and $\beta_e = \frac{2\pi}{\lambda_e}$

Then, the amplitude of the output voltage is given by,

$$V(l) = \frac{V(0)}{3} \exp\left[\sqrt{3}\,\pi NC\right]$$

The output power gain in decibels is given by,

$$A_p = 10 \log \left|\frac{V(l)}{V(0)}\right|^2$$

$$= 20 \log \left|\frac{\frac{V(0)}{3}\exp\left[\sqrt{3}\pi NC\right]}{V(0)}\right|$$

$$= 20 \log \left|\frac{\exp\left[\sqrt{3}\pi NC\right]}{3}\right|$$

$$= 20 \log \left|\frac{1}{3}\right| + 20 \log \left|\exp\left[\sqrt{3}\pi NC\right]\right|$$

$$= -9.54 + 20 \times \sqrt{3}\,\pi NC \log |e|$$

$$= -9.54 + 47.3NC \text{ dB}$$

$$\boxed{\therefore A_p = -9.54 + 47.3NC \text{ dB}}$$

Where,

NC – Numerical number.

Q48. Explain the significance of slow wave structure in the amplification process. List out the major differences between TWT and klystron.

Nov./Dec.-17, (R13), Q7(a)

(or)

Compare the performance of TWT with klystron amplifier. May/June-19, (R15), Q7(b)

(Refer Only Comparison between TWT and Klystron Amplifier)

Ans:

Significance of Slow Wave Structure

For answer refer Unit-1, Q43, Topic: Significance.

Comparison between TWT and Mentioned Klystron Amplifier

The differences between TWT and klystron amplifiers are as mentioned in table.

	Traveling Wave Tube (TWT)		Klystron Amplifier
1.	In TWT, the electrons interact with a travelling wave.	1.	In Klystron amplifier, the electrons interact with a standing wave.
2.	The interaction is distributed along the helical axis.	2.	The interaction between electrons and standing wave is localized.
3.	It can amplify over a broadband of frequencies, as there are no high 'Q' resonant circuits in TWT.	3.	In Klystron amplifiers, the amplification over broadband of frequencies is limited by high 'Q' resonant circuits.
4.	In TWT, the RF signal that interrupts the electron velocities is from the helix.	4.	In Klystron amplifiers, the RF signal that interrupts the electron velocities is from a resonant cavity.
5.	These are also called as broad band devices.	5.	These are also called as narrow band devices.
6.	These tubes can operate in a frequency range of 0.5 GHz to 95 GHz.	6.	These amplifiers can operate in a frequency range of 250 MHz to 100 GHz.
7.	The efficiency of these tubes is 5 to 20%.	7.	The efficiency of these amplifiers is 30 to 40%.
8.	These are used as low noise RF amplifier in broadband microwave receivers.	8.	These are used as power output tubes in UHF TV transmitters and radar transmitter.

Table

Q49. How oscillations are prevented in a Travelling Wave Tube?

Ans: Nov./Dec.-18, (R13), Q1(f)

As the slow wave structure of travelling wave tube is bidirectional, the signal can propagate in both the directions. When output of the coupler reflects the signal, it reflects backward along slow wave structure and serves as a feedback signal. This results oscillations in the travelling wave tube.

In travelling wave tube, oscillations are produced due to bunching. The bunching is the process in which electrons in the beam travel with higher speed than the wave travelling on the wire and interact with travelling wave fields due to velocity modulation.

In order to prevent oscillations in TWT, it is necessary to slow down the speed of bunches. This can be accomplished by transferring the electron energy to the travelling wave fields with correct polarity. This increases the amplitude of travelling wave along the TWT axis. As a result, the speed of electrons decreases and they cannot travel faster than the wave travelling on wire. Thus, no bunching takes place and no oscillations are produced.

The above drawback can be overcome by using a slow wave structure, which reduces the speed of travelling wave below speed of electrons in the beam.

Q50. What are the different modes of operation of TWT and explain them. Dec.-19, (R16), Q7

(or)

What are the different oscillating modes in TWT and explain them. May/June-19, (R15), Q7(a)

(or)

Explain why there are four propagation constants in TWT and derive equations to these propagation constants. Nov.-13, (R09), Q6(a)

Ans:

The electronic equation of the traveling wave tube is given by,

$$i = j\frac{\beta_e I_0}{2V_0(j\beta_e - \gamma)^2}E_1 \quad \text{... (1)}$$

Where,

i – Convention current in the electron beam

E_1 – Magnitude of the electric field in z- direction

β_e – Phase constant of the electron beam $= \frac{\omega}{v_0}$

I_0 – D.C beam current

γ – Propagation constant $= \alpha_e + j\beta_e$

V_0 – D.C beam voltage.

And the circuit equation of traveling wave tube is given by,

$$E_1 = -\frac{\gamma^2\gamma_0 z_0}{\gamma^2 - \gamma_0^2}\, i \quad \text{... (2)}$$

Where,

γ_0 – Propagation constant for $i = 0$

z_0 – Characteristic impedance.

The mode of travelling wave tube can be obtained by solving equations (1) and (2) simultaneously for the propagation constants. The solutions for propagation constants represents different modes of travelling wave in the tube. Basically, four different modes of travelling wave are possible in O-type travelling tube as there are four distinct solutions for propagation constants.

From equations (1) and (2),

$$(\gamma^2 - \gamma_0^2)(j\beta_e - \gamma)^2 = -j\frac{\gamma^2\gamma_0 z_0 \beta_e I_0}{2V_0} \quad \text{... (3)}$$

The above equation has four roots as it is a fourth order equation in γ. By using the approximation,

$$\gamma_0 = j\beta_e \quad \text{... (4)}$$

Equation (3) reduces to,

$$(\gamma^2 - (j\beta_e)^2)(j\beta_e - \gamma)^2 = -j\frac{\gamma^2(j\beta_e)z_0\beta_e I_0}{2V_0}$$

$$\Rightarrow \quad (\gamma + j\beta_e)(\gamma - j\beta_e)^3 = 2C^3\beta_e^2\gamma^2 \quad \text{... (5)}$$

Where,

C – Gain parameter of traveling wave tube

$$\text{and } C = \left[\frac{I_0 z_0}{4V_0}\right]^{1/3} \quad \text{... (6)}$$

The equation (5) represents that, there is one backward traveling wave corresponding to $e^{j\beta_e z}$ and three forward traveling waves corresponding to $e^{-j\beta_e z}$. Assume that the propagation constant of forward traveling waves as,

$$\gamma = j\beta_e - \beta_e C\delta \quad \text{... (7)}$$

Substituting the value of γ in equation (5), we have,

$$j\beta_e - \beta_e C\delta - j\beta_e)^3 (j\beta_e - \beta_e C\delta + j\beta_e) = 2C^3\beta_e^2(j\beta_e - \beta_e C\delta)^2$$

$$(-\beta_e C\delta)^3(2j\beta_e - \beta_e C\delta) = 2C^3\beta_e^2[-\beta_e^2 - (\beta_e C\delta)^2 - 2j\beta_e^2 C\delta]$$

Since $C\delta << 1$, neglecting all $C\delta$ and higher order $C\delta$ terms we have,

$$(-\beta_e C\delta)^3(2j\beta_e) = 2C^3\beta_e^2(-\beta_e^2)$$

$$\Rightarrow \quad \delta = (-j)^{1/3} \quad \text{... (8)}$$

The above equation can also be written as,

$$\delta = (-j)^{1/3} = e^{-j\left[\left(\frac{\pi}{2}+2n\pi\right)/3\right]} \; (\because n = 0, 1, 2) \quad \text{... (9)}$$

At $n = 0$, the first root δ_1 is,

$$\delta_1 = e^{-\frac{j\pi}{6}} = \frac{\sqrt{3}}{2} - \frac{j}{2} \quad \text{... (10)}$$

At $n = 1$, the second root δ_2 is,

$$\delta_2 = e^{\frac{-j5\pi}{6}} = -\frac{\sqrt{3}}{2} - \frac{j}{2} \quad \dots (11)$$

At $n = 2$, the third root δ_3 is,

$$\delta_3 = e^{\frac{j9\pi}{6}} = j \quad \dots (12)$$

Similarly, assuming the propagation constant for backward travelling wave as,

$$\gamma = -j\beta_e - \beta_e C\delta_4 \quad \dots (13)$$

Then the fourth root, δ_4 is obtained by, substituting equation (13) in equation (5)

$$\Rightarrow \quad \delta_4 = \frac{-jC^2}{4} \quad \dots (14)$$

Thus, the four propagation constant values are given by,

$$\gamma_1 = -\beta_e C\frac{\sqrt{3}}{2} + j\beta_e\left(1+\frac{C}{2}\right) \quad \dots (15)$$

$$\gamma_2 = \beta_e C\frac{\sqrt{3}}{2} + j\beta_e\left(1+\frac{C}{2}\right) \quad \dots (16)$$

$$\gamma_3 = j\beta_e\,(1 - C) \quad \dots (17)$$

$$\gamma_4 = -j\beta_e\left(1-\frac{C^3}{4}\right) \quad \dots (18)$$

The above four equations of propagation constant represents the four different modes of travelling wave. The wave corresponding to γ_1 is a forward wave and its amplitude grows exponentially with distance. This wave propagates with phase velocity lower than electron beam velocity and the energy flows from electron beam to the wave.

The wave corresponding to γ_2 is a forward wave and its amplitude decays exponentially with distance. This wave propagates with a phase velocity lower than electron beam velocity and the energy flows from wave to the electron beam.

The wave corresponding to γ_3 is a forward wave and its amplitude remains constant. This wave propagates with a phase velocity and there is no net exchange of energy.

The wave corresponding to γ_4 is a backward wave and there is no change in amplitude. This wave propagates with a phase velocity higher than the electron beam velocity and there is no net exchange of energy.

Q51. A TWT operates with following parameters, V_b = 2.5 kV, I_b =25 mA, Z_0 = 10 Ω, circuit length L = 50, f = 9 GHz. Find the gain parameter and power gain.

Ans:

Given that,

For a TWT,

$V_b = 2.5$ kV

$I_b = 25$ mA

$Z_0 = 10\,\Omega$

$L = 50$.

$f = 9$ GHz

Gain parameter, $C = ?$

Power gain, $A_p = ?$

The gain parameter of a TWT is given by the equation,

$$C = \left[\frac{I_0 Z_0}{4V_0}\right]^{1/3}$$

$$\Rightarrow \quad C = \left[\frac{I_b Z_0}{4V_b}\right]^{1/3}$$

On substituting corresponding values in above equation,

$$C = \left[\frac{25\times10^{-3}\times10}{4\times2.5\times10^3}\right]^{1/3}$$

$$= 2.92 \times 10^{-2}$$

$$\boxed{\therefore C = 2.92\times10^{-2}}$$

The expression for power gain of TWT is given by,

$$A_p = -\ 9.54 + 47.3\ NC$$

$$\Rightarrow -9.54 + 47.3 \times 50 \times 2.92 \times 10^{-2}$$

$$= 59.52$$

$$\boxed{\therefore A_P = 59.52\text{ dB}}$$

Q52. A helical TWT has diameter of 3 mm with 40 turns per cm. Calculate axial phase velocity and the anode voltage at which the TWT can be operated for useful gain.

Ans:

Given that,

For a helical TWT,

Diameter, $d = 3$ mm

Number of turns, $N = 40$ turns/cm

(i) Axial phase velocity, $(v_p) = ?$

(ii) Anode voltage, $(V_0) = ?$

(i) The axial phase velocity of a helical TWT is given by,

$$v_p = \frac{\omega}{\beta} = \frac{pc}{\pi d} \quad \dots (1)$$

Where,

p = Pitch of helix

$$p = \frac{10^{-2}}{40}$$

c = Velocity of light.

On substituting the corresponding values in equation (1),

$$v_p = \frac{\left(\frac{10^{-2}}{40}\right)\times\left(3\times10^8\right)}{\pi\times3\times10^{-3}}$$

$$= \frac{3\times10^9}{3\times\pi\times40} = \frac{10^8}{4\pi}$$

$$= 0.0796 \times 10^8 \text{ m/sec}$$

$$= 7.96 \times 10^6 \text{ m/sec}$$

$$\boxed{\therefore v_p = 7.96\times10^6\text{ m/sec}}$$

(ii) The expression for anode voltage of a TWT is given by,

$$V_0 = \frac{m}{2e}\times\frac{\omega^2}{\beta^2}$$

$$\Rightarrow \quad V_0 = \frac{m}{2e}\left(\frac{Pc}{\pi d}\right)^2$$

$$\Rightarrow \quad V_0 = \frac{m}{2e}v_p^2 \quad \dots (2)$$

On substituting the values of v_p, $e = 1.6 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg in equation (2),

$$V_0 = \frac{9.11\times10^{-31}}{2\times1.6\times10^{-19}}\times(7.96\times10^6)^2$$

$$= \frac{577.22}{3.2\times10^{-19}}\times10^{-19}$$

$$= 180.38 \text{ volts}$$

$$\boxed{\therefore \text{Anode Voltage}, (V_0) = 180.38\text{ volts}}$$

Q53. A TWT operates under following parameters, Beam voltage V_0 = 3 kV, beam current I_0 = 20 mA, characteristic impedance of helix Z_0 = 10 Ω, circuit length, N = 50 and frequency f = 10 GHz. Determine,

(i) Gain parameter

(ii) Output power gain in dB and

(iii) All Four propagation constants.

(Model Paper, Q3(b) | Nov./Dec.-18, (R13), Q6(b))

(or)

A TWT operates under following parameters beam voltage V_0 = 3 KV, beam current I_0 = 20 mA, characteristic impedance of helix Z_0 = 10, circuit length N_1 = 50 and frequency f = 10 GHz. Determine,

(i) Gain parameter

(ii) Output power gain in dB. Nov.-15, (R09), Q6(a)

(Refer Only (i) Gain parameter and (ii) Output power gain)

Ans:

Given that,

For a TWT,

Beam voltage, $V_0 = 3$ kV

Beam current, $I_0 = 20$ mA

Characteristic impedance, $Z_0 = 10\,\Omega$

Circuit length, $N = 50$

Frequency, $f = 10$ GHz

(i) Gain prameter, C = ?

(ii) Output power gain, A_p(dB) = ?

(iii) Propagation constant $\gamma_1 = ?, \gamma_2 = ?, \gamma_3 = ?, \gamma_4 = ?$

(i) The expression for gain parameter of a helix TWT is given by,

$$C = \left[\frac{I_0 Z_0}{4V_0}\right]^{1/3} = \left[\frac{20\times10^{-3}\times10}{4\times3\times10^3}\right]^{1/3}$$

$$= 0.0255$$

$$\boxed{\therefore C = 2.55\times10^{-2}}$$

(ii) The output power gain of helix TWT is given by,

$$A_p = -9.54 + 47.3\,NC$$

$$= -9.54 + 47.3 \times 50 \times 2.55 \times 10^{-2}$$

$$\therefore A_p = 50.77 \text{ dB}$$

(iii) The four propagation constants, $\gamma_1, \gamma_2, \gamma_3$ and γ_4 are given by,

$$\gamma_1 = -\beta_e C\frac{\sqrt{3}}{2} + j\beta_e(1 + C/2)$$

Where,

$$\beta_e = \frac{\omega}{V_0}$$

$$= \left[\frac{2\pi\times10^{10}}{0.593\times10^6\sqrt{3\times10^3}}\right]$$

$$\Rightarrow \beta_e = 1.93 \times 10^3 \text{ rad/m}$$

$$\therefore \gamma_1 = -1.93 \times 10^3 \times 2.55 \times 10^{-2} \times 0.87 + j1.93 \times 10^3\left[1+\frac{2.55\times10^{-2}}{2}\right]$$

$$\boxed{\therefore \gamma_1 = -42.82 + j1954.61}$$

$$\gamma_2 = \beta_e C\frac{\sqrt{3}}{2} + j\beta_e(1 + C/2)$$

$$= 1.93 \times 10^3 \times 2.55 \times 10^{-2} \times 0.87 + j1.93 \times 10^3\left(1+\frac{2.55\times10^{-2}}{2}\right)$$

$$\boxed{\therefore \gamma_2 = 42.82 + j1954.61}$$

$$\gamma_3 = j\beta_e(1 - C)$$

$$= j1.93 \times 10^3 (1 - 2.55 \times 10^{-2})$$

$$\boxed{\therefore \gamma_3 = j1880.78}$$

$$\gamma_4 = -j\beta_e(1 - C^3/4)$$

$$= -j1.93 \times 10^3\left[1+\frac{2.55\times10^2)^3}{4}\right]$$

$$\boxed{\therefore \gamma_4 = -j1930}$$

Q54. An O-type TWT operated at 2GHz. The slow wave structure has a pitch angle of 4.4 and attenuation constant of 2 Np/m. Determine the propagation constant of the travelling wave in the tube.

Ans: Nov./Dec.-18, (R13), Q7(b)

Given that,

For a O-type travelling wave tube,

Operating frequency, $f = 2$ GHz

Pitch angle of the slow wave structure, $\psi = 4.4°$

Attenuation constant, $\alpha = 2$ Np/m

Propagation constant, $\gamma = ?$

The phase velocity along pitch of the TWT is given by,

$$v_p = C \sin\psi$$

$$= 3 \times 10^8 \times \sin(4.4°) \qquad [\because C = \text{Velocity of light} = 3 \times 10^8 \text{ m/sec}]$$

$$= 23.016 \times 10^6 \text{ m/sec}$$

The phase constant, β is given by,

$$\beta = \frac{\omega}{v_p}$$

$$= \frac{2\pi f}{v_p} = \frac{2\pi\times2\times10^9}{23.016\times10^6}$$

$$= 545.984 \text{ rad/m}$$

Then, the propagation constant of the travelling wave tube is given by,

$$\gamma = \alpha + j\beta$$

$$= 2 + j545.984$$

$$= 545.988\angle 89.79° \text{ m}^{-1}$$

$$\boxed{\therefore \gamma = 545.988\angle 89.79° \text{ m}^{-1}}$$

Frequently Asked & Important Questions

Q1. What are the limitations of conventional tubes at microwave frequencies? REPEATED 2 TIMES

Ans: Refer Q1. (Dec.-19, (R16), Q1(e) | Nov./Dec.-16, (R13), Q1(e))

Q2. How microwave tubes are classified? REPEATED 2 TIMES

Ans: Refer Q3. (May/June-19, (R15), Q1(f) | Nov./Dec.-17, (R13), Q1(e))

Q3. In detail explain the limitations of conventional tubes at microwave frequencies. REPEATED 4 TIMES

Ans: Refer Q17. (March-21, (R16), Q4(a) | April/May-18, (R13), Q6(b) | May/June-13, R09, Q5(b) | Nov./Dec.-12, (R09), Q5(a))

Q4. Explain the working principle of two cavity Klystron with the help of applegate diagram. Also write the expression for velocity modulation and voltage gain. REPEATED 3 TIMES

Ans: Refer Q22. (March-21, (R16), Q4(b) | May/June-13, R09, Q6(b) | Nov.-13, (R09), Q5(a))

Q5. Compose and explain about two cavity Klystron amplifier and derive its Bunching process. REPEATED 4 TIMES

Ans: Refer Q24. (Oct./Nov.-20, (R16), Q5(a) | April/May-18, (R13), Q6(a) | Nov./Dec.-16, (R13), Q6 | Nov./Dec.-12, (R09), Q5(b)

Q6. Explain briefly about the construction and operation of reflex klystron oscillator. REPEATED 2 TIMES

Ans: Refer Q30. (Nov.-15, (R09) Q5(b) | May/June-13, R09, Q5(a))

Q7. How the oscillations are generated in reflex klystron and explain bunching process with apple gate diagram and also derive the equation for efficiency. REPEATED 2 TIMES

Ans: Refer Q31. (Dec.-19, (R16), Q6 M[10] | March-21, (R16), Q5(a))

Q8. What is the significance of slow wave structure? Explain the amplification process in TWT. REPEATED 5 TIMES

(March-21, (R16), Q5(b) | Nov./Dec.-18, (R13), Q7(a) | Nov./Dec.-17, (R13), Q7(b) |

Ans: Refer Q45. Nov./Dec.-17, (R13), Q9(a) | Nov./Dec.-16, (R13), Q7(b)

Q9. Explain the significance of slow wave structure in the amplification process. List out the major differences between TWT and klystron. REPEATED 2 TIMES

Ans: Refer Q48. (Nov./Dec.-17, (R13), Q7(a) | May/June-19, (R15), Q7(b)

Q10. What are the different modes of operation of TWT and explain them. REPEATED 3 TIMES

Ans: Refer Q50. (Dec.-19, (R16), Q7 | May/June-19, (R15), Q7(b) | Nov.-13, (R09), Q6(a)s

Q11. A TWT operates under following parameters, REPEATED 2 TIMES

Beam voltage $V_0 = 3$ kV, beam current $I_0 = 20$ mA, characteristic impedance of helix $Z_0 = 10\ \Omega$, circuit length, $N = 50$ and frequency $f = 10$ GHz. Determine,

(i) Gain parameter

(ii) Output power gain in dB and

(iii) All Four propagation constants.

Ans: Refer Q53. (Nov./Dec.-18, (R13), Q6(b) | Nov.-15, (R09), Q6(a))

Q12. Explain the gain bandwidth product limitation in conventional vacuum tubes.

Ans: Refer Q19. Important Question

Q13. Explain Reentrant cavities.

Ans: Refer Q23. Important Question

Q14. Formulate Power Output and Efficiency in Reflex Klystron amplifier.

Ans: Refer Q32. Important Question

Q15. Derive the expressions for repeller voltage and electronic efficiency of reflex krystron.

Ans: Refer Q33. Important Question

Q16. Draw the mode curves of reflex klystron and derive the relation between mode number and repeller in reflex klystron.

Ans: Refer Q36. Important Question

Q17. Explain about electronic and mechanical tuning in reflex klystron.

Ans: Refer Q38. Important Question

Q18. Discuss the significance and types of Helix TWTs.

Ans: Refer Q43. Important Question

Q19. Explain with neat sketch, the principle of operation of a TWT amplifier and write the equations for the maximum voltage gain and efficiency.

Ans: Refer Q46. Important Question

Q20. How oscillations are prevented in a Travelling Wave Tube?

Ans: Refer Q49. Important Question