ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION

Microwave Valves

INTRODUCTION

Microwave valves are used to generate or amplify electrical signals at radar frequencies. The three types used in Artillery Radars are the Magnetron, Klystron and Travelling Wave Tube. The three types of valve have different operating parameters and are generally not interchangeable. All types can be designed to generate frequencies in the 1 - 30 GHz range at peak power levels of order Mega-Watts, although no single valve can cover the entire range of powers and frequencies. Figures One and Two illustrate two types of Klystron, of very different capabilities.

The three types of valve were invented many years ago (used in wartime radars) and modern devices are based upon them, with some improvements. These devices come in all sizes and are widely used wherever high powers are required at high frequencies (including micro-wave ovens, TV transmitters and radar). This handout describes the general features of these valves and explains their basic operating principles.

LIMITATIONS OF CONVENTIONAL VALVES

Audio and radio circuits operate at frequencies below about one hundred Mega-Hertz, where the wavelength of the electro-magnetic wave (EM Wave) is much larger than the circuitry within the equipment.

Figure J.03-1: A High-Power Klystron, with Four Cavities, Used for TV Transmission

Consequently, the wavelength is not an important feature in the design of the circuit at these relatively low frequencies. The periodic time of the signal is of order tenths of micro-seconds and the components in the circuits can react in that sort of time. (E.g. time constant of capacitor/inductor.)

Conductor dimensions and wavelength: at each point along a wire that is a few cm in length and carrying an audio frequency signal (wavelength many kilometres), the signal is the same - just as the surface of the Earth appears flat when only a small fraction of it is visible. At radar frequencies, say 10 GHz, the wavelength is only 3 cm. This means that if there is a large positive signal at one point in a wire then there could be an equally large negative signal (anti-phase) only 1.5 cm further along the wire. Since the dimensions of a conventional valve and its circuitry are comparable with that then this is one reason why the conventional valve does not work well at radar frequencies. Both positive and negative signals are within the valve at the same time and can cancel each other.

Transit Time: at radar frequencies, the periodic time of the signal is of order 100 ps (or 0.000 1 μs). Normally, electrons respond to an alternating current by moving first one way and then the next. But on this time-scale, the electrons would not have time to move very far in one direction before they began to move back again. In fact, there is not enough time for them to pass through (transit) a conventional valve or transistor.

Skin Effect: as the frequency of an alternating current increase then the current is affected by its own magnetic field. This causes it to flow only in the outermost skin of the conductor and the resistance increases significantly. At radar frequencies, a significant fraction of the power in a circuit can be wasted (in the form of heat) by this extra resistance.

Reactance: at radar frequencies, the reactance of an inductor ($X_L = 2\pi fL$) becomes very large whilst the reactance of a capacitor ($X_C = 1/(2\pi fC)$) becomes very small. At these frequencies, even the inductance of a straight wire and the capacitance between two adjacent wires become significant and interfere with the operation of the circuit.

The combined effect of the above factors is to

Figure J.03-2: The Klystron used in Rapier B2

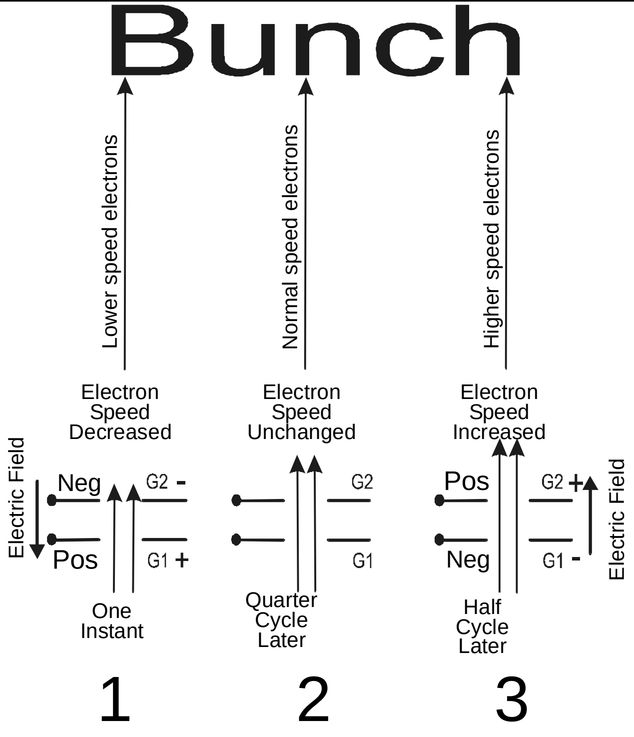


Figure J.03-3: Three Stages in the Process of Velocity Modulation, Leading to Bunching

make ordinary circuits become ineffective at radar frequencies - especially when high power is required but also when a very small signal has to be amplified.

VELOCITY MODULATION

Since the high frequencies of radar signals makes it difficult to get the electrons to move backwards and forwards then it is necessary to adopt a different approach. Instead, starting with a steady flow of electrons, passing though a vacuum like a jet of water from a hose pipe, their velocities are changed. Some will be slowed down and some will be speeded up - this is done alternately, by the electric field of a sine-wave.

Downstream from the velocity modulator, no electrons will actually reverse but there will be some slow-moving electrons followed by some fast moving electrons. The useful effect occurs when the fast-moving electrons catch-up with the slow-moving electrons, to form a 'bunch'. The voltage used to produce the beam of electrons might be as much as 10 kV, whereas the signal voltage, that causes the velocity modulation, might only be a few Volts (although it could be more).

To change the velocity of these electrons, they are made to pass between two perforated metal plates, G_1 and G_2, as shown in Figure Three. The metal plates are connected to the radar frequency that we want to amplify, for example: 3 GHz.

The top diagram (1) shows the stream of electrons passing though when the left-hand plate is positive. The electrons are slowed down by the electric field between the plates and energy passes from the electrons to the field. These electrons continue towards the right-hand side at a relatively slow speed.

The middle diagram (2) shows the situation after a quarter-cycle of the input frequency. The signal is momentarily at zero so there is no electric field between G1 and G2, so the electrons pass through without any change of velocity. (Note that $^1/_4$ cycle at 3 GHz corresponds to a time interval of 0.083 ns or 0.000 083 µs.)

The bottom diagram (3) shows the stream of electrons passing through when the left-hand plate is negative. This is now one half-cycle later than the top diagram. The electric field between the plates causes the electrons to accelerate and some energy passes from the signal to the electrons.

Overall, virtually no energy has passed from the input signal to the electrons. This is because it has both given up energy (to cause some electrons to go faster) and taken back energy (to cause some electrons to slow down). However, the system is designed so that the faster-moving electrons will catch-up with the slower-moving electrons after a short distance, in the region marked 'Bunch' in the Figure.

The time intervals are very small and it is necessary to have very fast moving electrons and to keep the gap between the metal plates as small as possible. This is to allow time for some electrons to pass through before the field changes.

THE KLYSTRON - BUNCH FORMATION

The word 'Klystron' is derived from the German word for a bunch. The formation of bunches of electrons is the key to velocity modulation and the operation of the Klystron. You have seen in the previous section that some electrons were slowed down as they passed between the metal plates and that some electrons were speeded up. As the beam continues along its path then the faster moving electrons will catch up with the slower ones and form a bunch of electrons. This might occur a few centi-metres further downstream. This bunch of electrons is moving very quickly and is, of course, negatively charged.

The bunch of electrons is moving very quickly and, consequently, contains a significant amount of kinetic energy. Each cycle of the input signal will produce a new bunch and the electron flow a few cm downstream from the metal plates will pulsate at the input frequency.

RESONANT CAVITIES

These are covered in the BST Handout entitled 'Waveguides'. The 'rhumbatron' cavity has dimensions that enable it to resonate at radar frequencies.

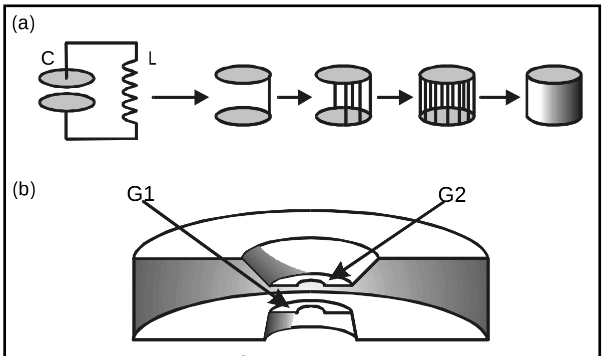


Figure J.03-4:
a. Evolution of LCR Resonant Circuit into a Cavity
b. A Practical Resonant Cavity

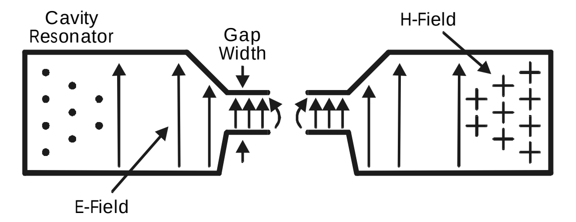


Figure J.03-5: The Electric (vertical) and Magnetic (horizontal) Fields in a Cavity Resonator

Figure Four (a) indicates how the cavity is derived from an LCR parallel circuit. The main feature of this cavity is that it resonates (stores energy) over a narrow range of frequencies.

The electron beam is made to pass up through the central hole in the cavity. As shown in Figure Four (b), the metal plates ‘G1’ and ‘G2’, shown in Figure Three correspond to the bottom and top surfaces in the middle of the cavity. The cavity is ‘pinched’ in the middle to increase the effect of the electric field as the intensity of an electric field between two metal surfaces increases when the distance between them is reduced. This is also useful as the stream of electrons will be able to cross the narrow gap in a shorter time. A diagram showing the electric and magnetic fields at one instant (when the top plate is positive) is shown in Figure Five.

EXTRACTING ENERGY FROM THE BEAM

If a second cavity is placed downstream from the first and positioned at the spot where the bunches form then the electron flow though its centre will pulsate as each bunch passes. When a bunch passes through the pinch-point of the cavity then it induces a field between the metal surfaces and this field propagates into the cavity as an E- Wave. The wave passes radially outwards, into the cavity and reflects from the edge, returning to the centre. The dimensions of the cavity are chosen so that the EM-Wave returns to the centre just in time to collect energy from the next bunch of electrons. This is why a resonant cavity must be used - to get the timing right.

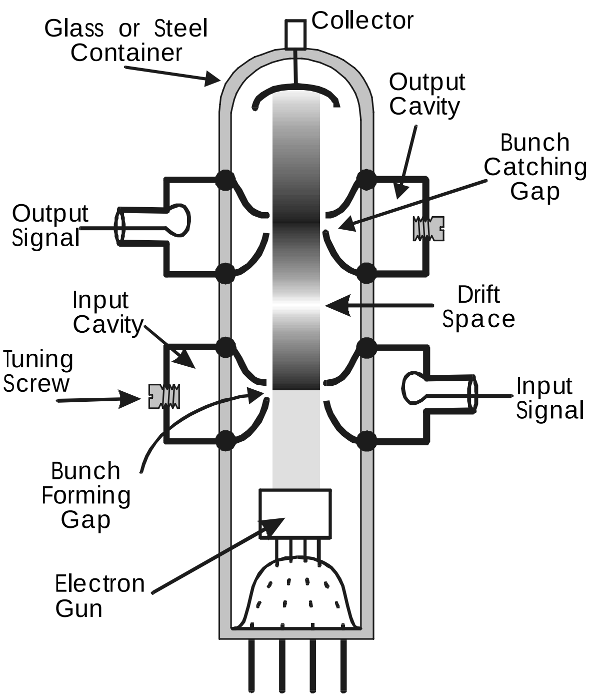


Figure J.03-6: Schematic Diagram of a Two-Cavity, Klystron Amplifier Valve

The effect on the cavity is similar to what happens when a parent pushes a child on a swing – each push causes the amplitude of the swing to increase (resonance) and a very big amplitude can be built up from a series of pushes. Provided that the pushes occur at the resonant frequency of the swing.

If the second cavity has the same resonant frequency as the first (which is also the same as the input frequency and the frequency at which the bunches occur) then a significant fraction of the energy in a bunch is transferred into the second cavity as each bunch passes through.

The bunch then continues on, moving more slowly since it has lost kinetic energy to the cavity, and the electrons strike a metal ‘collector’ from where they continue their journey around the circuit. Their remaining energy causes the collector to heat up significantly and some form of cooling is often required. Around 50% of the energy is wasted as heat at the collector - some form of cooling is usually required, otherwise the ‘used’ electrons will melt the collector. This cooling might be by air-blast (Rapier B2) or liquid cooling (television transmitters).

Magnetic Focusing: the Klystron valve often features permanent magnets or solenoids (electro-magnets) situated along its length to ‘focus’ the beam of electrons. This is needed because the electrons each carry negative charge and, consequently, they repel each other. This repulsion would cause the beam to diverge and weaken the bunches, but the effect of the magnetic field is to push them back towards the centre of the device.

Electro-static Focusing: the beam can also be kept in the centre of the device by making the cavities and other internal components much more negative than the beam - since electrons are negative then they will be repelled by other negatives and the beam can be confined to the centre. Effectively, this produces an electrostatic field that pushes the electrons towards the centre of the device.

KLYSTRON COMPONENTS

Figure Six shows a schematic diagram of a Klystron valve. Klystrons are used as amplifiers in TV transmitters and radar transmitters (e.g. Rapier FSB2, Surveillance radar); smaller klystrons can also be used as amplifiers and oscillators in radar receivers. The parts of the Klystron and their functions are listed below:

- **Electron Gun**: the electron beam is produced, at the bottom of the valve, by a device called an ‘electron gun’. Depending on the operating power, this might produce in a radar transmitter as much as tens of Amps at many thousands of Volts or, in a radar receiver, as little as a few milli-Amps at a few hundred Volts.

- **Input Cavity**: the signal to be amplified enters here - its frequency must correspond to the resonant frequency of the cavity.
- **Tuning Screw**: this is adjusted in or out to change the size of the cavity and, hence, its resonant frequency.
- **Bunch-Forming Gap**: the input signal is concentrated across here and its electric field causes changes in the velocities of the electrons passing though.
- **Drift Space**: the space between the two cavities is where the electrons 'drift' along, the faster moving electrons catching up with the slower moving ones.
- **Bunch-Catching Gap**: positioned where the bunches will be at their most intense, the bunches that pass though here give up much of their kinetic energy into the cavity.
- **Output Cavity**: resonates at the operating frequency and transfers the energy from the bunches to the output waveguide or co-axial cable.
- **Collector**: the beam of electrons ends here and its remaining kinetic energy causes it to heat up significantly.

MULTI-CAVITY KLYSTRON

To extract more power from the beam of a Klystron, it is necessary to make the bunches more intense. This can be achieved by placing a number of additional cavities between the input and the output cavities. Commonly, there are four cavities used. The intermediate cavities have no external connection, they receive their signal from passing bunches and are so arranged that they cause more velocity changes so that the bunches are intensified. The Klystron used in FSB2 has four cavities.

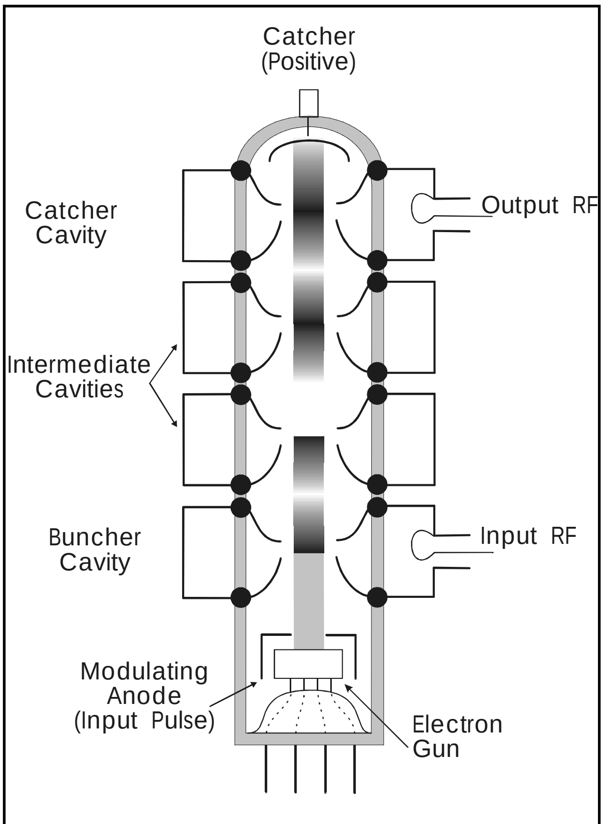


Figure J.03-7: A Klystron with Four Cavitities

Stagger Tuning: if each cavity is tuned to exactly the same frequency then the valve would not be able to provide 'frequency agility', as it would be limited to the resonant frequency. When there are four cavities then each can be tuned to a *slightly* different frequency from the others and the valve is then able to operate over a wider frequency range.

The Klystron used in Rapier B2, Model PT6014/5, pictured in in Figure Two and shown diagramatically in Figure Seven, has a nominal frequency of 3.174 GHz and can operate over a bandwidth of 5 MHz (± 2.5 MHz). By adjusting the tuning screws, the centre frequency can be changed by ± 78 MHz. You can download this information from the manufacturer's web site, www.tmd.co.uk (search for PT6014 or PT6015).

LIMITATIONS OF THE KLYSTRON

The Klystron requires resonant cavities to function and these might, typically, have a bandwidth of only a few MHz. This means that the ability of the Klystron to provide frequency agility is very limited. The multi-cavity Klystron can be 'stagger-tuned' (see above) to widen bandwidth but this is at the expense of gain.

The Klystron is also prone to generate noise and this can degrade the signals that it is being used to amplify. The Klystron can be designed so that it produces minimum noise at its operating frequency and this alleviates most of the problem (at the expense of frequency agility).

The trend in modern military radars is to operate using a very wide bandwidth and this is difficult to achieve using a Klystron. Consequently, the Klystron is often rejected in favour of either a travelling-wave tube (FSC) or solid-state device (Cobra) in the latest radars.

MODULATION

In a pulsed radar, it is necessary to operate the Klystron during the outgoing pulse (e.g. for 10 μs) and then to turn it off whilst the receiver listens for the echo. The device that does this is called a modulator. The modulating signal is a rectangular pulse and it can be applied to either:

- **Grid**: a wire mesh or metal cup, placed near to the heated cathode, through which the electron beam must pass en-route to the Anode and Catcher. If a large negative signal (e.g. -100 V) is applied here then the electrons are blocked.
- **Anode**: a metal plate or cup, with a central hole, through which the electrons pass en-route to the Catcher. A large positive signal (e.g. +1 kV) here directs the electrons through whilst a negative signal (e.g. -2 kV) blocks them.

The beam must be switched off between pulses to limit the production of heat at the Catcher. The Klystron used in Rapier B2 uses negative pulses at the Anode to modulate the Klystron.

THE MAGNETRON

The Magnetron is a device for generating signals at radar frequencies. It differs from the Klystron in that the Magnetron cannot be used as an amplifier. Consequently, the Magnetron has no RF Input - it just generates its own RF signal at a frequency determined by its resonant cavities.

The Magnetron is constructed from a block of solid Copper (for conductivity and heat transfer) as shown in Figure Eight. The cavities are cut into the solid Copper block and there might be six, eight or ten. At the centre of the block is a heated 'Cathode' that emits electrons in large numbers (several Amps is a typical value). The cathode is held negative by several thousand Volts during operation and the anode is usually connected to Earth.

Without any other influence, the electrons from the hot cathode would move at high speed across the space between cathode and anode and form an electric current (dc). The paths of these electrons would be like the spokes of a bicycle wheel.

The Magnetron, however, has a very powerful permanent magnet fitted so that its magnetic field fills the space between cathode and anode, as shown in Figure Eight. (This field is called an 'Axial' field because it runs along the central axis of the magnetron.) The effect of this field is to cause the electrons to travel in a spiral path and the field is so strong that they cannot reach the anode. Four example paths are illustrated in Figure Nine.

Effect of the Cavities: The four paths shown in Figure Nine cross the mouth of a cavity and energy will be transferred from the electrons to the cavity. Just as a swing that is pushed one way will swing back in the oppiste direction after one half-cycle, so the electric and magnetic fields in the cavities will reverse after one half-cycle and reverse again after one more half-cycle. With careful design, it can be arranged that more electrons come past during the next cycle and the oscillations within each cavity build up rapidly to very large levels. Most electrons eventually reach the anode after passing several cavities and delivering their energy to each. Figure Nine shows electrons approaching four cavities, the parts of the Anode labeled 'A' will be positive as the electron approaches whilst parts 'B' will be negative. This causes the electron to slow down and causes the transfer of energy into the cavities 'C'. Few electrons approach part 'B' because it is Negative at this time. After one half-cycle, the polarities will reverse and the energy transfer will occur at an adjacent cavity.

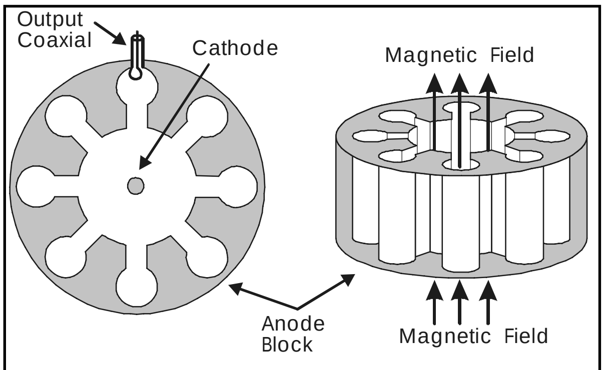


Figure J.03-8: Magnetron Cavities and Layout

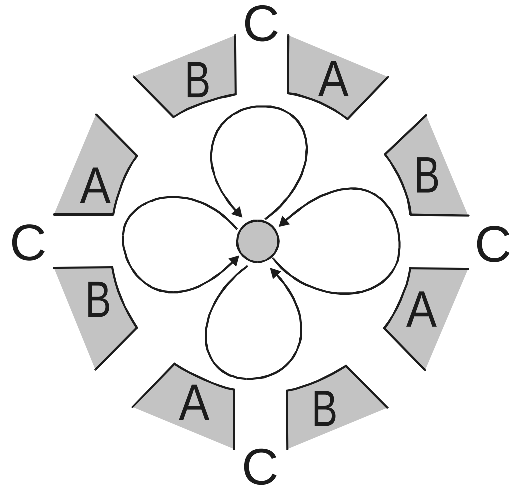


Figure J.03-9: Spiral Path of Electrons in Axial Field

Some electrons are slowed down so much that their spiral paths leads them back to the cathode and their kinetic energy can be usefully employed to help to maintain the required operating temperature. Initially, the cathode is heated by a separate, electrical heating element but this is sometimes switched off after a few seconds as electron bombardment is sufficient to maintain the temperature of the cathode.

Output Connection: the cavities are all linked together by the Copper block and only one needs a connection for the output. Magnetrons are on/off devices and are used to generate high power signals at radar frequencies (e.g. the Command Transmitter and, DN181 Tracking Radar of Rapier.) They cannot be used to amplify as there is no means of connecting any input signal. Domestic micro-wave ovens use a magnetron to generate their micro-waves for cooking.

Magnetron Tuning: a screw or metal vane can be inserted into a cavity to change its size (slightly) and, hence, to adjust the frequency of operation. Some designs have a cavity that contains a metal vane that is 'wiggled' by a piezo-electric transducer to provide an continually-varying output frequency. The eight cavities cannot practically be made to have the exactly the same dimensions (they expand with temperature – so any attempt at precision would have limited effect) and any of the cavities can dominate and determine the operating frequency. Consequently, Magnetrons tends to jump at random from one frequency to another, depending on the current dominant cavity.

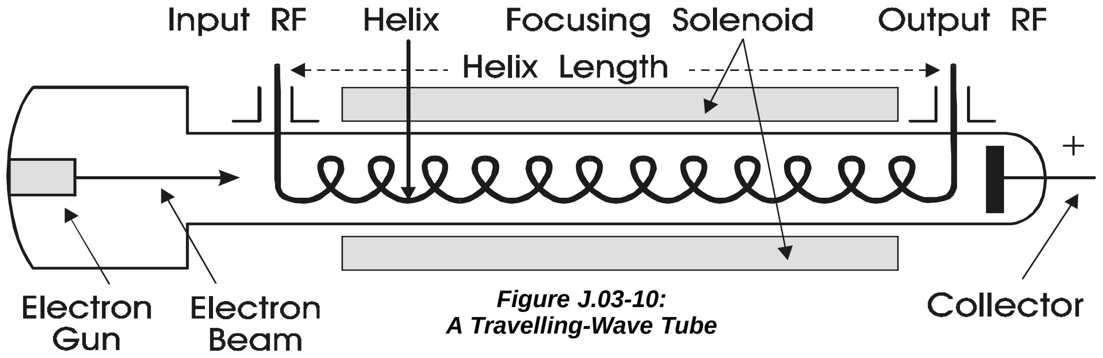


Figure J.03-10:
A Travelling-Wave Tube

TRAVELLING-WAVE TUBE (TWT)

Both Klystron and Magnetron devices use resonant cavities as an integral part of their operation. Where the device has to operate over a wide range of frequencies then neither can practically be used. The TWT has no resonant cavities so it is not constrained to operate over a narrow range of frequencies - its bandwidth is much wider than that of the Klystron or Magnetron.

The TWT, like the other two valves, uses the principle of velocity modulation. Electrons are slowed down by the electric field of the signal and the kinetic energy that the electrons lose is transferred to the signal. As the electrons slow down then the signal gains power.

The construction of a TWT is shown in Figure Ten. The tube might be up to 1 metre in length. The beam of electrons, moving from left to right, will be moving with a velocity that is about $^{1}/_{10}$ of the speed of light. The input signal, which also enters from the left, would normally move at about the speed of light along the tube. This would not allow energy to be transferred from electrons to signal because the signal must travel more slowly than the electrons (just like a surfer cannot get ahead of his wave - or he would lose the crest).

In the TWT, the input signal is slowed down by making it flow around a helix (like a screw-thread). The pitch of the helix is arranged so that the input signal moves around it at the velocity of light (at the circumference) but along it at a velocity slightly less than that of the electron beam. Now the electrons are travelling along the tube at a higher velocity than the input wave and energy can be transferred as the wave slows down some electrons and takes their kinetic energy. Some electrons will also be able to take energy from the signal and gain velocity.

The fact that some electrons are slowed down also causes bunches to form as the faster-moving electrons catch up with the slower-moving ones. The construction of the tube is such that the signal takes energy from the bunches (many electrons slowed) but gives out energy at positions where there are no bunches (a few electrons speeded up). Consequently, much more is gained by the signal than is lost and, overall, the signal gains energy and power. TWTs can operate in the MW range.

There are no cavities in a TWT so it can operate over a wide range of frequencies to permit operation with frequency-agile radar systems such as Rapier FSC. When used in radar receivers then it can be used as a very effective amplifier of small signals as it has a very low noise figure.

OSCILLATORS

An amplifier takes in a signal and send it out with increased power, but it does not make a signal of its own. An oscillator has no input, other then dc power, but it produces an output of its own. Generally, the output frequency is determined by the resonant frequency of some components within the oscillator.

To convert a device that can amplify into an oscillator then part of its output is connected back to the input. A public address (PA) system that produces a ‘howl’ when its microphone is place too close to a loudspeaker is performing the same action. The output signal goes back to the input where it is re-amplified to become more output and that, in turn returns to the input in an everlasting loop.

Of course, the loop must be started when the oscillator is required to produce an output. The signal that starts the oscillation is random noise - this exists in all circuits and at all frequencies. Some tiny part of the noise will be at the resonant frequency and that will usually be sufficient to initiate the self-sustaining loop.

A Klystron Oscillator is illustrated in Figure Eleven. The feedback path is on the right-hand side of the diagram. Almost any amplifier can be made to oscillate by this type of feedback and some sort of cavity or resonant circuit is needed to determine the frequency of operation.

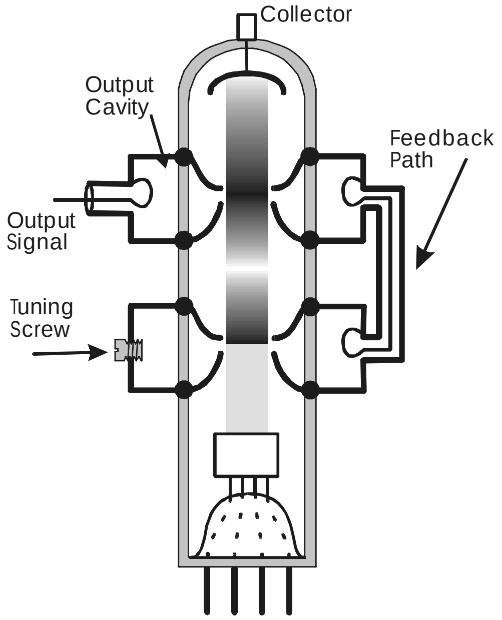


Figure J.03-11: Schematic Diagram of a Klystron Amplifier Valve with Feedback to make it Oscillate

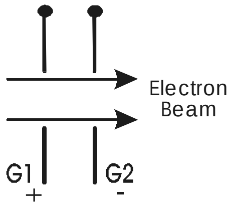
SELF-TEST QUESTIONS

1. The ‘skin effect’ causes:

  a. more resistance at low frequencies.
  b. more resistance at high frequencies.
  c. less inductance at high frequencies.
  d. less current at the surface of a conductor at high frequencies.

2. A beam of electrons is passing from left to right, between two perforated metal plates, in the diagram below. The left-hand plate, G1, is positive and the right-hand plate, G2, is negative. The effect on the electron beam will be to cause it to:

  a. speed up.
  b. spiral.
  c. reverse.
  d. slow down.



3. The principal effect of velocity modulation is to cause electrons to:

  a. speed up.
  b. form bunches.
  c. reverse.
  d. slow down.

4. As a bunch of electrons passes through the output cavity of a Klystron then the electrons in the bunch:

  a. speed up and gain energy.
  b. oscillate.
  c. reverse.
  d. slow down and lose energy.

5. A multi-cavity Klystron would have each cavity tuned to a slightly different frequency in order to make the valve operate:

  a. at its resonant frequency.
  b. over a wider range of frequency.
  c. over a narrower range of frequency.
  d. as an oscillator.

6. The magnets used in a Klystron:

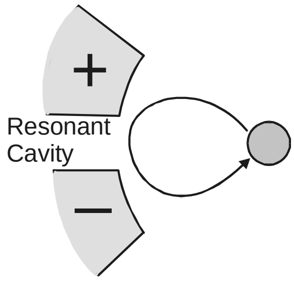
  a. slow down some electrons to form the bunches.
  b. maintain the focus of the beam.
  c. speed up some electrons to form the bunches.
  d. direct the electrons across the cavities.

6. The purpose of the permanent magnet in a magnetron valve is to:

  a. slow down some electrons to form the bunches.
  b. maintain the focus of the beam.
  c. speed up some electrons to form the bunches.
  d. direct the electrons across the front of the cavities.

7. The diagram shows the path of an electron in a Magnetron. At the time when the electron passes across the mouth of the cavity, the electric polarity is as shown. As the electron passes it will:

  a. take energy from the cavity.
  b. speed up.
  c. give energy to the cavity.
  d. be attracted by the negative side of the cavity.



8. The micro-wave valve that can only be used as an oscillator (and not as an amplifier) is the:

  a. Multi-cavity Klystron.
  b. Two-cavity Klystron.
  c. Travelling-Wave Tube.
  d. Magnetron.

9. The primary purpose of the helix in a Travelling-Wave Tube is to:

  a. cause the input signal to go more slowly along the length of the tube.
  b. speed up the electrons.
  c. slow down the electrons.
  d. focus the beam of electrons.

10. The micro-wave valve that features both low noise and wide bandwidth is the:

  a. Multi-cavity Klystron.
  b. Two-cavity Klystron.
  c. Travelling-Wave Tube.
  d. Magnetron.

Answers

1. Page 1 . . . . .(b)	6. Page 3 . . . .(b)
2. Page 2 . . . . .(d)	7. Page 4 . . . .(c)
3. Page 2 . . . . .(b)	8. Page 6 . . . .(d)
4. Page 3 . . . . .(d)	9. Page 5 . . . .(a)
5. Page 4 . . . . .(b)	10. Page 6 . . .(c)

Teaching Objectives		Comments

J.03.01 Describe the limitations of conventional circuits at micro-wave frequencies

J.03.01.01	Describe the problems caused by ‘transit time’ effects.	Not enough time for the electrons to cross the device.
J.03.01.02	Describe the problems caused by the skin effect.	Too much loss in ordinary cables.
J.03.01.03	Describe the problems caused by extreme values of X_L and X_C at micro-wave frequencies.	X_L too high and X_C too low.
J.03.01.04	Describe the problems caused by the short wavelength in relation to the size of the circuit.	

J.03.02 Describe the concept of velocity modulation

J.03.02.01	Describe how electrons can be accelerated/decelerated as they pass through an alternating electric field.	
J.03.02.02	Describe the formation of bunches.	In general terms, drift-space.
J.03.02.03	Describe the exchange of energy between the electric field and the electron stream.	

J.03.03 Describe the properties of simple, resonant cavities.

J.03.03.01	Describe how a resonant cavity is derived from an LCR circuit.	Rhumbatron
J.03.03.02	Sketch the electric and magnetic fields in a resonant cavity.	
J.03.03.03	State that the resonant frequency depends on the dimensions of the cavity.	Small cavity – high frequency.
J.03.03.04	Describe how the resonant frequency can be changed using vanes or slugs.	As used in DN181, Rapier B2.

J.03.04 Describe the operating principle & properties of a klystron

J.03.04.01	Identify the component parts of a klystron and explain their function.	Electron gun, buncher cavity, intermediate cavities, output cavity, collector.
J.03.04.02	Describe the operation of a klystron as an amplifier.	In terms of velocity modulation, multi-cavity, stagger-tuning.
J.03.04.03	Compare the performance of a klystron against that of the other micro-wave valves.	Noisy, frequency stable, large, small magnets for focusing.

Teaching Objectives		Comments

J.03.05 Describe the operating principle & properties of a magnetron

J.03.05.01	Identify the component parts of a magnetron and explain their function.	Cathode, permanent magnet, anode cavities, output cavity.
J.03.05.02	Describe the operation of the magnetron as an oscillator.	Electron paths, self-heating of cathode.
J.03.05.03	Compare the performance of a magnetron against that of the other micro-wave valves.	High power, unstable frequency, long life, heavy magnet.

J.03.06 Describe the operating principle & properties of a travelling-wave tube (TWT)

J.03.06.01	Identify the component parts of a TWT and explain their function.	Electron gun, focusing magnets, helix, collector
J.03.06.02	Describe the operation of a TWT as an amplifier/Oscillator	In terms of velocity modulation.
J.03.06.03	Compare the performance of a TWT against that of the other micro-wave valves.	Low noise, wide bandwidth, long & thin.