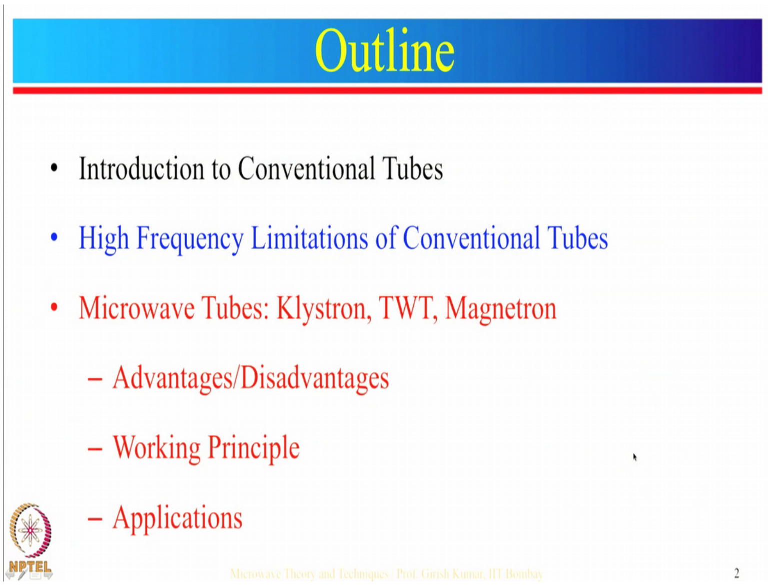
Microwave Theory and Techniques
Prof. Girish Kumar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Module - 08
Lecture - 38
Microwave Tubes – I: Linear Beam Tubes– Two Cavity Klystron

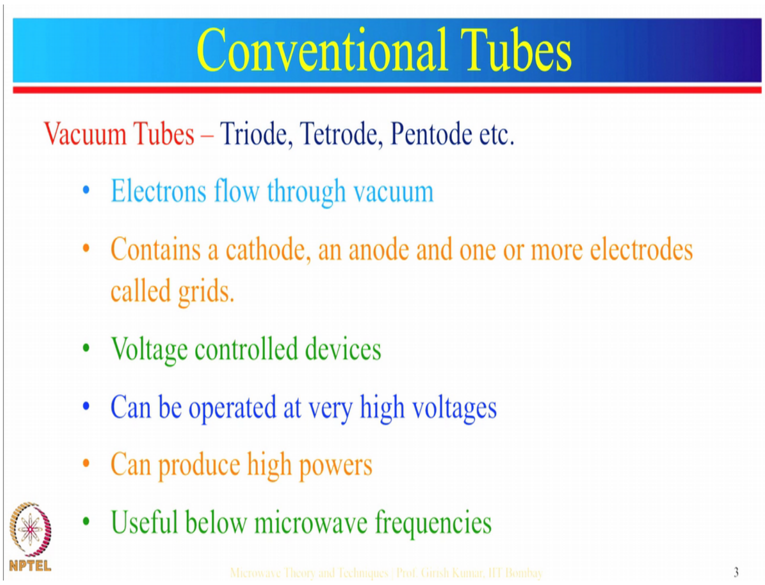
Hello my name is Rajbala, I am pursuing PhD under the guidance of Professor. Girish Kumar. I will take few lectures on Microwave Tubes.

(Refer Slide Time: 00:32)



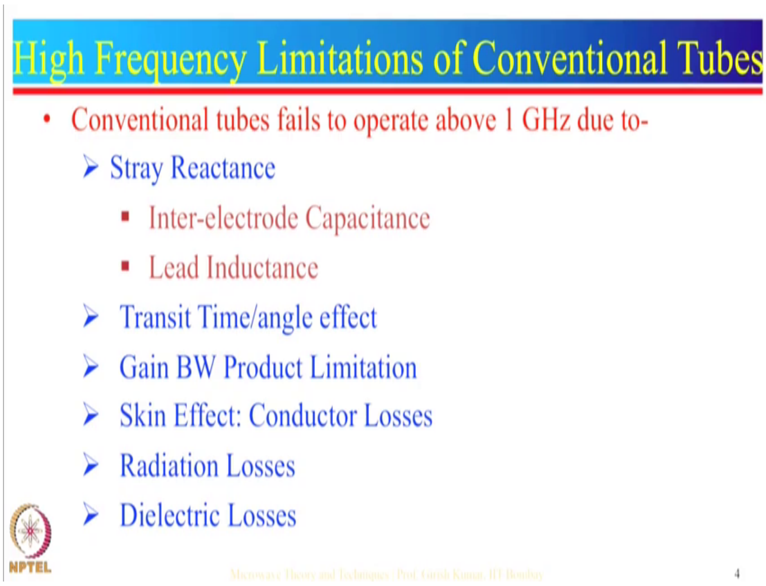
The outline to cover this topic is; first I will start with introduction to conventional tubes followed by high frequency limitations of conventional tubes. Then I will discuss microwave tubes such as Klystron, Travelling Wave Tubes and Magnetrons. I will discuss their advantages, disadvantages, working principle and applications. So, let us begin.

(Refer Slide Time: 00:59)



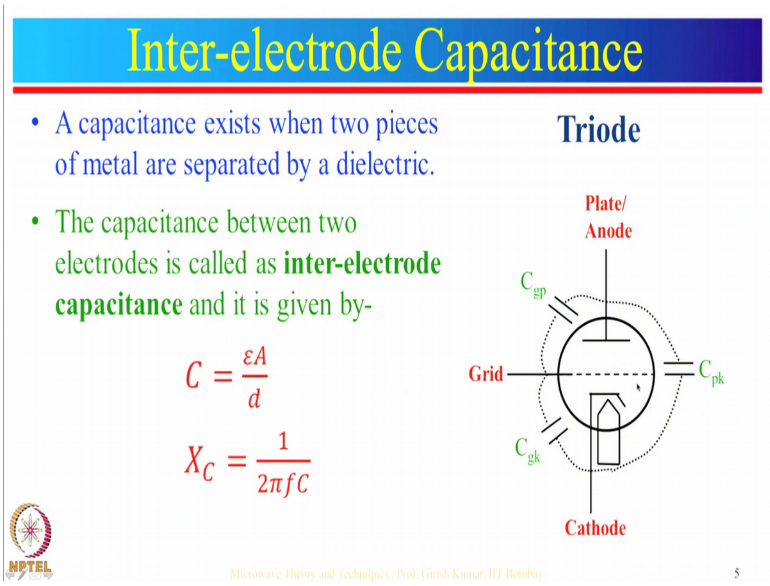
The vacuum tubes such as triodes, tetrodes, pentodes etcetera; these are the examples of conventional tubes. And what are vacuum tubes? Vacuum tubes are the electronic devices in which electrons flow through vacuum from one electrode to another electrode. Generally speaking, vacuum tubes contains one cathode, one anode and one or more than one grids. These grids are used for controlling actions. Since, vacuum tubes are voltage controlled devices, so the grid voltages will be the controlling voltages. The vacuum tubes can be operated at very high voltages and these can generate high powers also.

(Refer Slide Time: 01:55)



But these vacuum tubes are useful below microwave frequencies only, because at microwave frequencies these conventional tubes will have some limitations such as inter-electrode capacitance, lead inductance, transit time effect, gain bandwidth product limitation and so on. I will discuss these limitations one by one. So, let us start with inter-electrode capacitance.

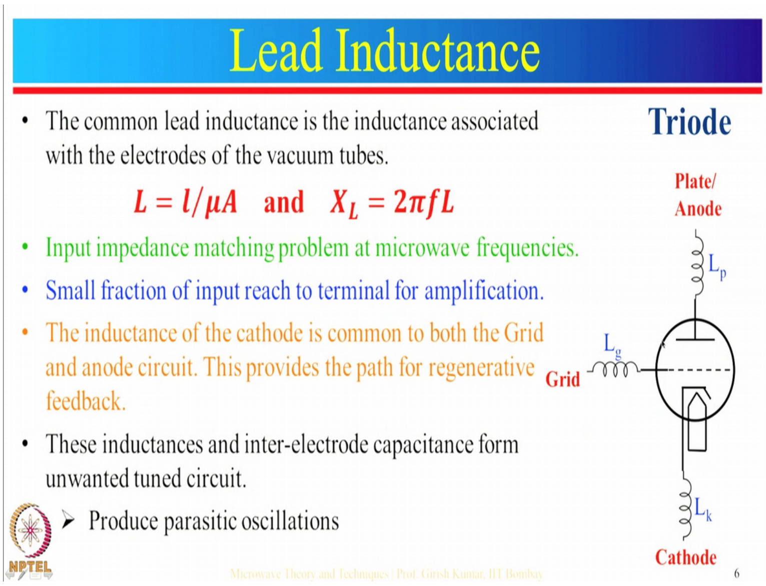
(Refer Slide Time: 02:22)



Now, the first question is; where does a capacitance exist. A capacitance exists between two metal plates separated by a dielectric. Now, take an example of vacuum tube triode. So, in triode there are three electrodes one is grid, then plate and other is cathode. These electrodes are separated by a dielectric air which has dielectric constant one. So, there must exist capacitance between the electrodes of the triode. So, these capacitances are known as inter-electrode capacitances. Generally, though capacitance of though two plates separated by a dielectric is given by C is equal to epsilon A by d, where epsilon is the dielectric constant of the material A is the area of the plates, and d is the distance between the plates.

And the capacitive reactance is given by X C is equal to 1 upon 2 pi f c; that means, X C is inversely proportional to frequency. So, as frequency increases capacitive reactance decreases. And at microwave frequencies this capacitive reactance can be approximated by a short circuit. Now, applying this concept to this triode; so let us say at microwave frequencies capacitance between grid and anode is approximated by a short circuit, then whatever voltage is present at the grid that will be directly transfer to anode. So, there will be no amplification action. So, the gain of this device triode will decrease.

(Refer Slide Time: 04:13)

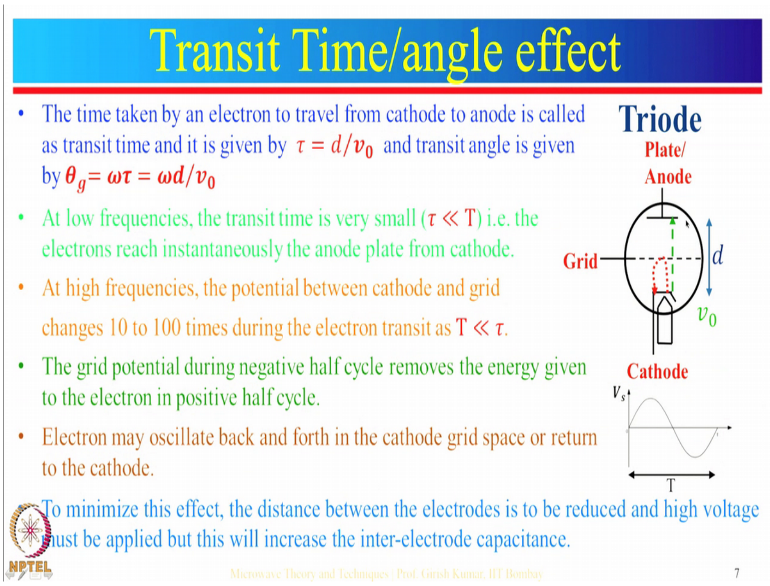


Now, move onto the next limitation of conventional tubes that is lead inductance. Now, again the same question where does an inductance exist an inductance exists for a conducting wire. For example, for this triode there are three electrodes. So, these are the wires of the electrodes. So, there must exist inductance for these electrodes. So, there are three inductances L grid, L plate and L cathode. Now, in general the inductance of a conductive wire is given by capital L is equal to small 1 divided by mu A, where small l is the length of the conducting wire, mu is the permeability of the material, and A is the cross section area of the conducting wire.

And the inductive reactance is given by X L is equal to 2 pi f l; that means, X L is directly proportional to frequency. So, as frequency increases inductive reactance increases. And at microwave frequencies inductive reactance is very high and because of this high impedance, there will be impedance matching problem at input port as well as at output port. So, because of this impedance mismatching there will be reflections from the input port and output port. And because of these reflections whatever input we give to the device triode, the small fraction of that input will reach to the terminal for amplification. And hence, the gain of this device decreases.

We can explain this with another way also that the inductance of cathode is common to both grid and plate. So, this will provide feedback from output to input; and because of this feedback the gain of this triode decreases. Now, one more thing these lead inductances with inter-electrode capacitances from unwanted resonant circuits. And these resonant circuits produced parasitic oscillations and these parasitic oscillations will import the performance of the device.

(Refer Slide Time: 06:42)



Now, let us move onto the next limitation which is transit time effect what is a transit time that transit time of an electron is the time taken by an electron to travel from cathode to anode. Let us a foot triode the distance between anode and cathode is d, and the average velocity of the electron is small v naught, then the transit time will be distance divided by velocity; that means, tau is equal to d divided by small v naught. And the transit angle will be theta g is equal to omega tau, which is equal to omega d divided by small v naught.

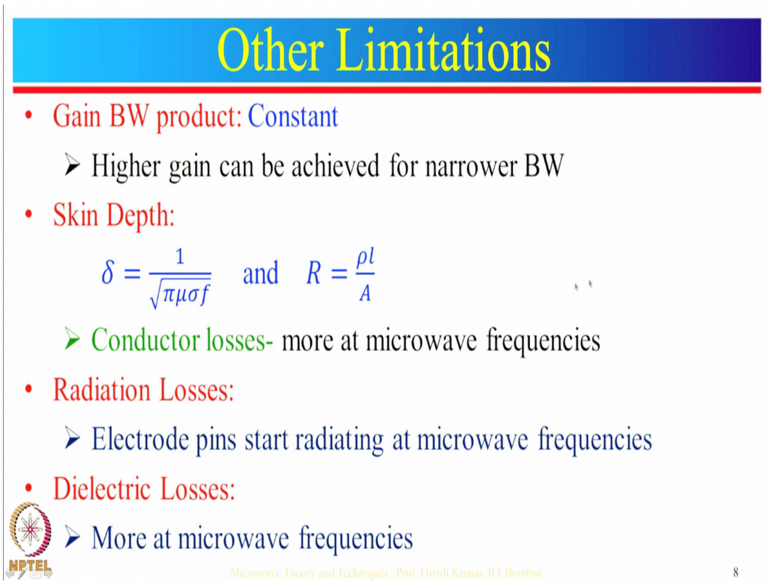
Now, let us say this is the input voltage given to this device, where this capital T is the time period of the input signal. Now, before analyzing the effect of frequency let us see what happens if input voltage of this device changes. So, for positive voltages, the electrons will get potential energy to move from cathode to anode, but as voltage changes from positive to negative; the electrons will be attracted towards the cathode.

So, now let us see what happens if frequency changes. So, for low frequencies the time period of the input signal is very very greater than the electron transit time.

So, as the voltage applied then electron will get potential energy in the positive half cycle of the input, and they will move to the anode instantaneously before the input changes from positive to negative. But for higher frequencies, the time period of the input signal is very very less than the electron transit time that means, the input changes 10 to 100 times in one transit time of an electron. So, as soon as electrons get potential energy in positive half cycle of the input that starts moving towards the anode, but before it could reach to the anode, the input changes from positive to negative. And the negative half cycle that energy will be taken back and electron will be attracted towards the cathode and the electron will move something like this shown by redline.

Now, again positive half cycle comes and electron will move towards anode, and then again negative half cycle, so like this process goes on. And because of this process electron may oscillate back and forth in the cathode grid space or return back to the cathode. To minimize this affect the distance between the electrodes should be reduced and high voltages should be applied, but because of this inter-electrode capacitance will increase.

(Refer Slide Time: 09:31)

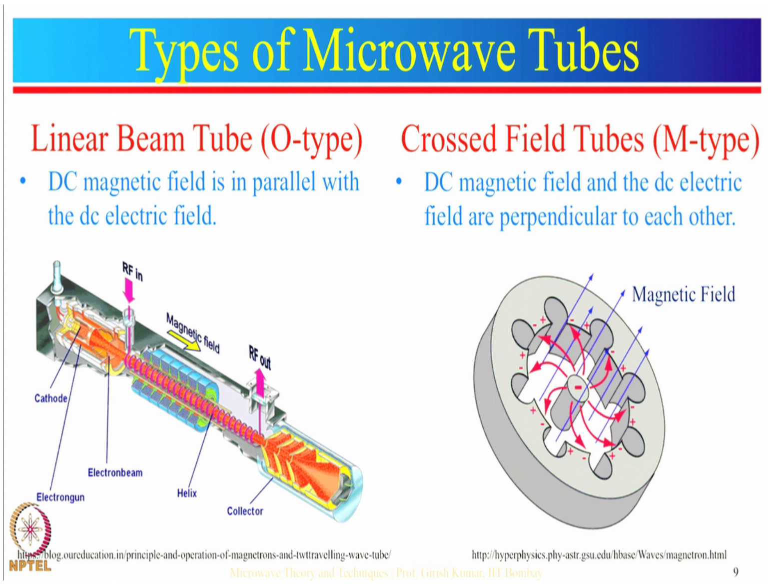


Now, let us move onto the next limitation which is gain bandwidth product limitation. At microwave frequencies the conventional tubes start resonating; and for a resonant circuit gain bandwidth product is constant. So, to achieve higher gains we should compromise for bandwidth. This limitation of conventional tubes can be overcome by microwave tubes by using reentrant cavities or the slow wave structures. I will discuss these things later in the slides.

Now, the next limitation is skin depth. So, skin depth of a conductor is given by delta is equal to 1 upon under root pi mu sigma f, where mu is the permeability of the material, sigma is the conductivity of the conductor f is the frequency. So, skin depth is inversely proportional to square root of frequency. So, as frequency increases, skin depth decreases. At microwave frequencies this skin depth is very very small. So, we can say that at microwave frequencies most of the current flows through the surface or we can say effective area for current flow decreases. And the resistance of a conductor is given by R is equal to rho l by A, where rho is the resistivity of the material, l is the length of the conductor, A is the area of the conductor. So since, this effective area has been reduced by skin depth, hence the resistance of that conductor will increase. And because of this increased resistance there will be more conductor losses at microwave frequencies.

Now, next limitation is radiation losses. At microwave frequencies electrode pills of the vacuum tubes start radiating. So, because of this radiation, there will be radiation losses. The last limitation is dielectric losses. Since, as frequency increases the loss tangent of a dielectric material increases, so there will be more dielectric losses at microwave frequencies. So, this is all about the limitations of conventional tubes at microwave frequencies.

(Refer Slide Time: 12:09)

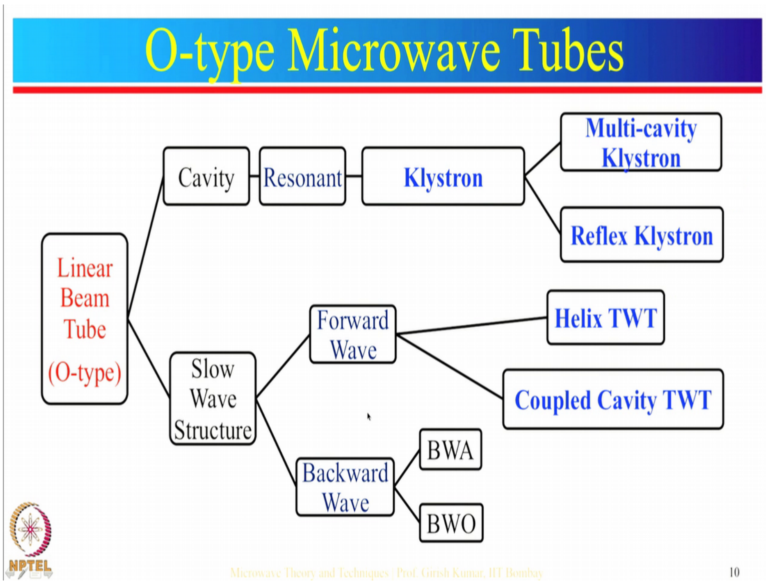


Now, I will start microwave tubes. Microwave tubes are of two types. One is linear beam tube or O-type tube and the second one is crossed field tubes or M-type tubes. In M-type tubes DC magnetic field and the DC electric fields are perpendicular to each other as shown by this figure.

So, in this the electric field is in this plane and magnetic field is normal to this plane. I will discuss in detail later in the linear beam tubes DC magnetic field is parallel to the DC electric field. And in these type of tubes electrons are injected from the cathode and they will get potential energy from the DC beam voltage. And after getting this potential energy, the electrons will move to the microwave interaction region, and of the potential energy is converted to the kinetic energy. And in microwave interaction region electrons are accelerated or decelerated by the microwave field present there.

And because of this acceleration and deceleration, electrons form bunches as they move down the tube. And these bunch electron induced current to the output structure. And after that they give their energy to the microwave field present in the output structure. And after that they will be collected by the collector. So, this is how the electrons move from cathode to collector in a linear beam tube or this is the basic working of a linear bean tube.

(Refer Slide Time: 13:59)

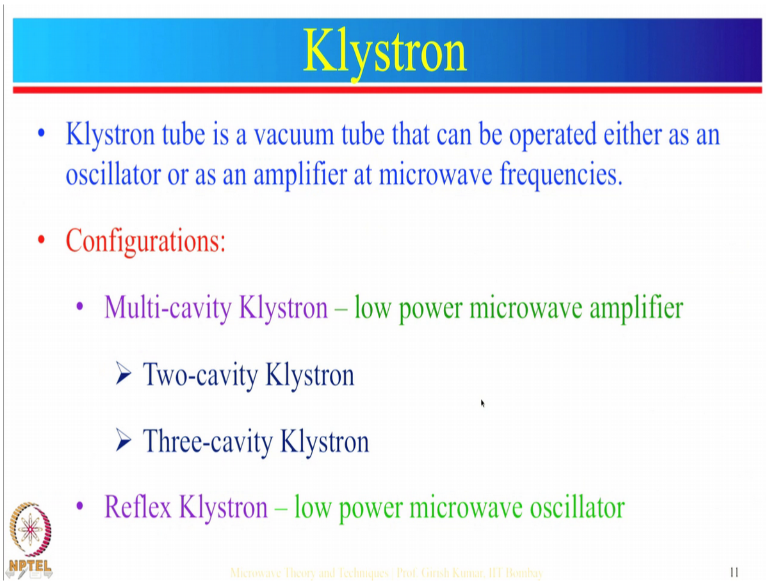


Now, I will discuss classification of linear beam tubes. Linear beam tubes are of two types, cavity type and slow wave structure type. Cavity type structures are the resonant structures; and slow wave structures are the non resonant structures. Each one of these structures have some advantages and some disadvantages which I will discuss after covering these two structures.

In the slow wave structure, the name slow waves comes from the fact that these type of structures are used to slow down the electromagnetic wave. Now, the question is why we need to slow down the electromagnetic wave, because electron moves much much slower than the electromagnetic wave. So, electrons do not get sufficient time to interact with the microwave fields. So, to increase the time of interaction of electrons, we need to decrease the velocity of electromagnetic waves.

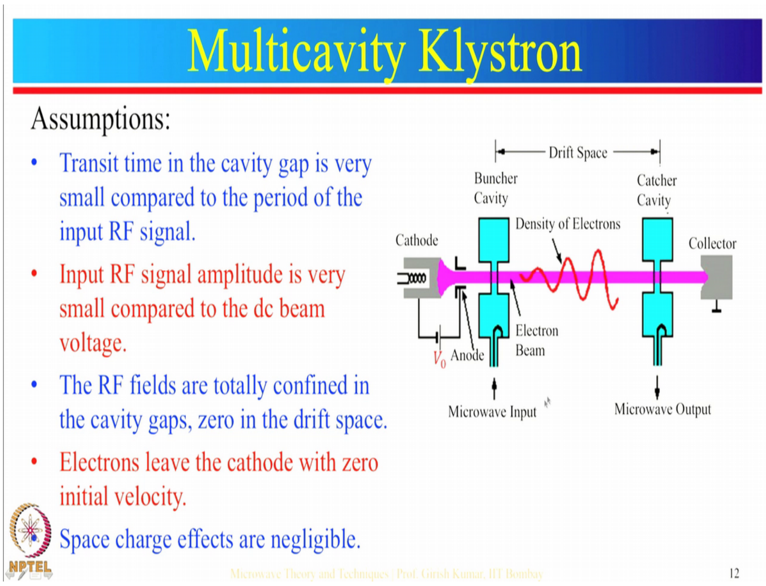
So, slow wave structures are of two types depending upon the movement of electrons in the tube. First one is forward wave; and another one is backward wave. The examples of forward wave slow wave structures are helix travelling wave tubes and coupled cavity travelling wave tubes. And the backward wave structures are backward wave amplifiers and backward wave oscillators. Now, I will discuss these microwave tubes one by one.

(Refer Slide Time: 15:54)



So, let us start with klystron. So, klystron tube is a vacuum tube that can be operated either as an oscillator or as an amplifier at microwave frequencies. In klystron, there are two configurations one is low power microwave amplifier which is multi-cavity klystron; and another one is low power microwave oscillator which is reflex klystron.

(Refer Slide Time: 16:24)

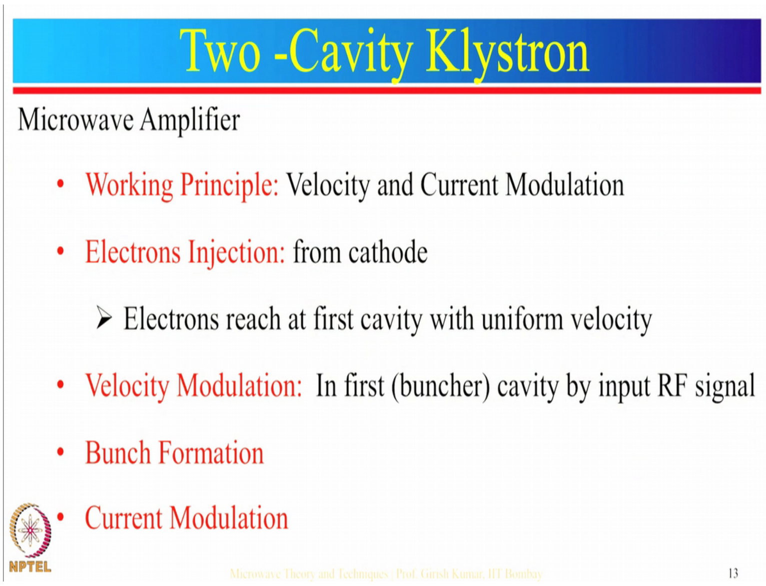


So, let us start with multicavity klystron first. So, this is the basic diagram of a two-cavity klystron. So, before analyzing the working of multicavity klystron, we need to understand some assumptions made while analyzing the working of multicavity klystron/ The first assumption is that the electron transit time in the cavity gap is very very small as compared to the period of input RF signal. This assumption is made to neglect the back and forth movement of electron in the cavity gap or we can say oscillation of the electron in the cavity gap.

And the next assumption is input RF signal amplitude is very small as compared to the dc beam voltage. The reason for this is also the same as the last one. The next assumption is that the RF fields are totally confined in the cavity gaps, and zero in the drift space. This assumption is made, so that the velocity of electrons is modulated only in this cavity gap. So, there will be no velocity modulation in the drift space and the kinetic energy of the electrons will be transferred to output structure only or output cavity only.

Now, next assumption is electrons leave the cathode with zero initial velocity and after that they will move with uniform velocity. And the last assumption is effects of space charges are negligible.

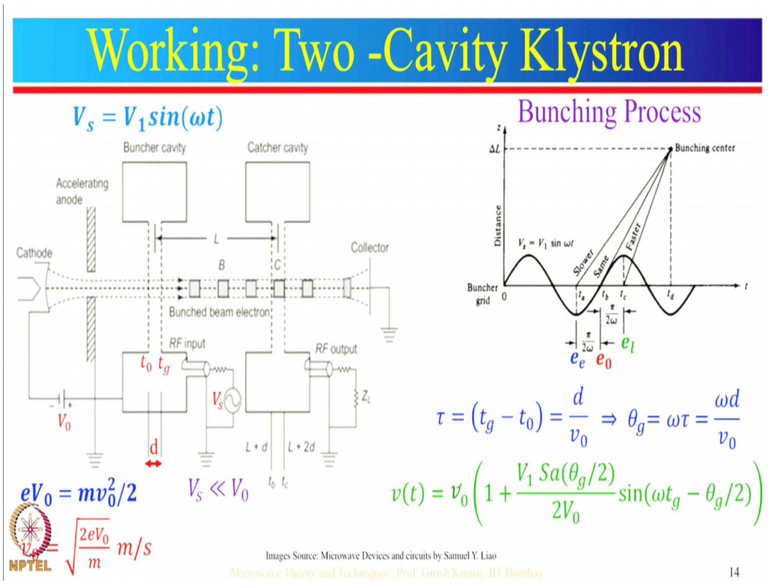
(Refer Slide Time: 18:15)



Now, let us see two-cavity klystron a two-cavity klystron is a widely used microwave amplifier, which works on the principle of velocity and current modulation. In this there are two cavities; one is input cavity which is also called as buncher cavity and another one is output cavity which is also called as catcher cavity. Electrons in this klystron are injected from the cathode, and all these injected electrons will reach to the first cavity with uniform velocity. And in the first cavity the velocity of these electrons will be modulated by the input RF signal present there in the first cavity. And this is called as velocity modulation.

And because of this, velocity modulation electrons form bunches as they drift down the tube and that is called as bunch formation. And because of this bunch formation, the density of the electron in the catcher cavity varies periodically with time that means the electron beam contains ac component of the current that is known as current modulation. So, after passing through second cavity, all the electrons will give up their kinetic energy to the microwave fields present in the second cavity. And because of that their velocity will be reduced, and they will be collected by the collector.

(Refer Slide Time: 19:55)



Now, see its working in more detail now. So, this is a cathode, this is the collector, this is the input cavity or buncher cavity, this is the catcher cavity or output cavity. So, input RF signal is applied here and output signal will be given to this. So, these gaps are of input cavity and output cavity; these gaps are called as microwave interaction region.

So, in this region electrons will be interacted with the microwave field present there in the cavity this is the dc beam voltage which is given to the cathode. So, electron will be injected from this cathode, and they will move with uniform velocity small v naught is equal to under root 2 e capital V naught divided by m, where e is the electron charge, capital V naught is the dc beam voltage, and m is the mass of the electron.

This velocity can be derived by equating the potential energy and kinetic energy of the electrons. Now, what is potential energy of the electron, potential energy of the electron is e v naught. And what is the kinetic energy of the electron, kinetic energy of the electron is half of m v naught square where capital V not is dc beam voltage and small v not is the velocity of electrons.

Now, let us say the average time to reach to this buncher cavity is t naught, and average time to leave the cavity is t g, then what will be the transit time transit time will be tau is equal to t g minus t naught. And let us say the gap of this cavity is d, then the transit time will be t g minus t naught is equal to distance divided by velocity d divided by small v naught. And what will be the transit angle, transit angle will be theta g is equal to omega tau which is equal to omega d divided by small v naught.

Now, what will happen to these electrons in this cavity gap? To answer this question we need to see the bunching process. So, let us say this vertical axis represent the distance along the tube. And these horizontal axis represent the time and this wave is input signal. Now, let us say we have a reference electron e naught which reaches the cavity. At this point of time at this point of time the input RF signal is 0. So, because of this there will be no change in the velocity of this electron.

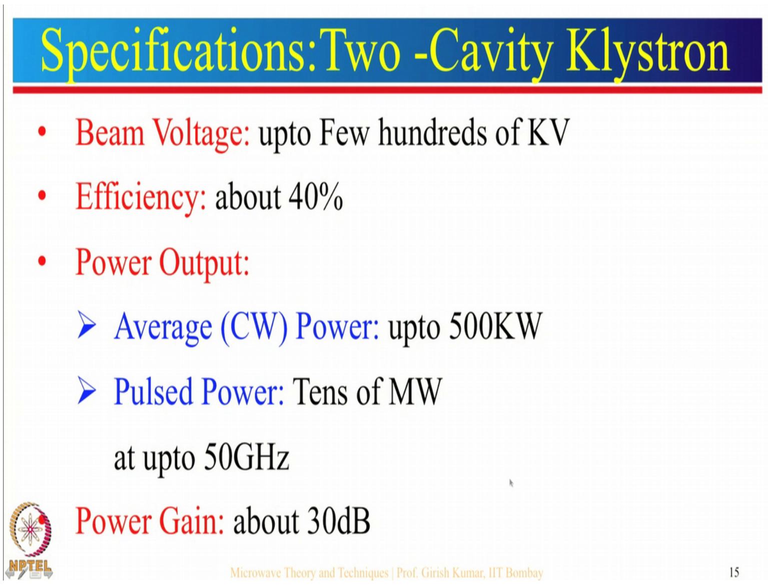
So, let us say this electron reaches the delta L point or delta L distance after time t d minus t b. Let us say we have another electron early electron that reaches the cavity at this point of time when the input signal is negative maxima. So, for this electron, the velocity of this electron will be reduced to the minimum. And this will move with velocity less than the reference velocity or this will take more time than the reference electron. So, let us say this reaches to delta L point after t d minus t a time, which is also equal to the time taken by the reference electron plus this time. So, this time is pi by 2 omega or t by 4, where t is the time period of the input signal. So, time taken by the early electron to reach to this point will be time taken by the reference electron plus one-fourth of the time period of the input RF signal.

Let us say we have one more electron that is late electron that reaches to the buncher cavity at this point of time when the input RF signal is positive maxima. So, its velocity is increased to the maximum. And it will take less time as compared to the reference electron. So, let us say it takes t d minus t c time to reach to this point. So, this time will be time taken by the reference electron minus this time. So, this time is t by 4. So, time taken by late electron will be time taken by reference electron minus one-fourth of the time period of the input RF signal. So, this is how these electrons will be bunched after this distance delta L.

And velocity of these electrons can be calculated by this formula only v is equal to under root two e capital V divided by m, where the capital V voltage for these electrons will be different that will be dc beam voltage v naught plus voltage across this gap that will vary for different electrons. So, that velocity can be derived by using this formula at that comes out to be v of t is equal to v naught 1 plus V 1 sampling function theta g divided by 2 divided by 2 V naught into sin omega t g minus theta g divided by 2. So, this is the modulated velocity of these electrons after they pass through the buncher cavity.

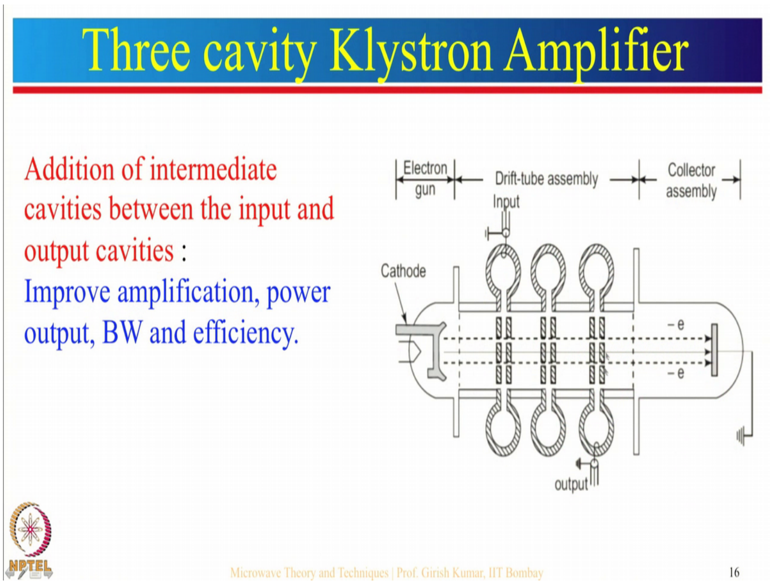
So, after passing through the buncher cavity they will form bunches as they drift down into the tube. And in the catcher cavity, the face of the gap voltage is maintained such that the electron beam encounter retarding phase, so that these electrons gives their kinetic energy to this catcher cavity. And after giving up their kinetic energy, the velocity of these electrons will be reduced and they will be collected by the collector. So, this is the basic working of a two-cavity klystron.

(Refer Slide Time: 27:05)



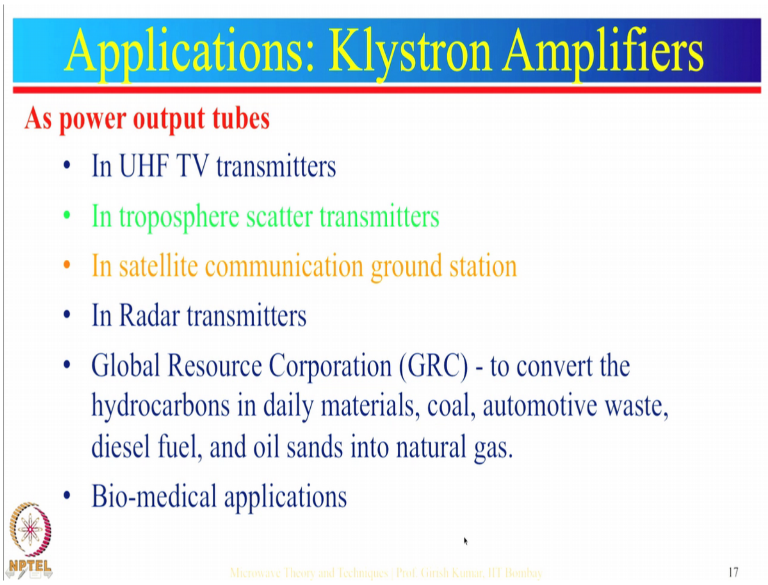
Now, let us see the specifications of practically available two-cavity klystrons beam voltages up to few hundreds of kilovolts can be given. The efficiency of practically available two-cavity klystron in up to 40 percent; and the power outputs are average continuous wave power output is up to 500 kilo volt and pulsed power is up to tens of megawatt. The typical gain of these klystrons is about 30 dB. And to increase the gain further the reentrant cavities can be used between input cavity and output cavity.

(Refer Slide Time: 27:43)



For example, in three cavity klystron, there are three cavities. One is input cavity, another one is output cavity and between these two there is a reentrant cavity. This reentrant cavity increases the output power bandwidth and efficiency of this three cavity klystron amplifier.

(Refer Slide Time: 28:06)



Now, the applications of klystron amplifiers as the power output tubes are in UHF TV transmitters, and troposphere scatter transmitters in satellite communication ground stations, in radar transmitter or we can say wideband high power communication systems. And in Global Resource Corporation, klystron amplifiers are used to convert hydrocarbons into natural gases. And these klystron amplifiers are also used in many labs in the world to generate high powers for testing. And these amplifier also have some medical applications such as in radiation oncology. So, this is all about the applications of klystron amplifiers.

Now, just to summarize what we discussed today is first we discussed conventional tubes then their high frequency limitations. After that we discuss the classifications of microwave tubes, linear beam tubes we discuss in detail. And then multi cavity klystron and their assumptions while analyzing the multicavity klystrons, and working principle of two-cavity klystron. Then we discussed specifications of practically available two-cavity klystron and applications of these klystron amplifiers.

In the next lecture, I will discuss reflex klystron and travelling wave tubes in detail.

Thank you.