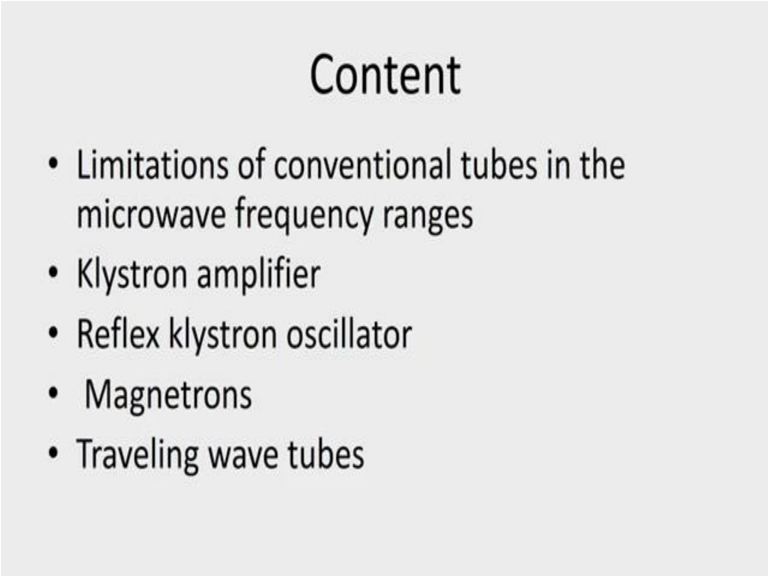
Microwave Engineering
Professor Ratnajit Bhattacharjee
Department of Electronics & Electrical Engineering
Indian Institute of Technology Guwahati
Lecture 28 - Microwave Tubes

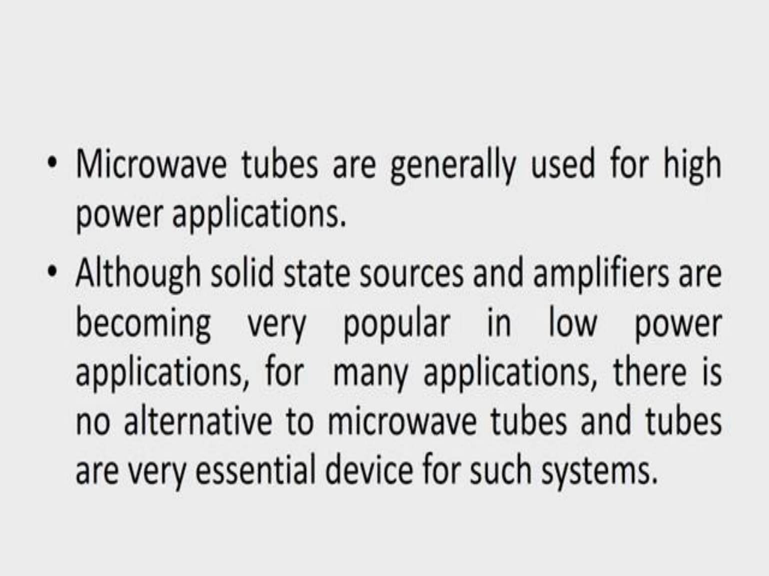
(Refer Slide Time: 0:38)



We start a new module, microwave tubes, and in this module we cover the following contents: we discuss the limitations of conventional tubes in the microwave frequency ranges. By conventional tubes, we mean the low-frequency tubes such as triode or tetrode. We then discuss klystron amplifier, in fact we discuss the specialized tubes which were developed for microwave frequency application, and klystron is one such tube, so we discuss klystron amplifier.

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. Next, we will consider another device which is called a magnetron and magnetrons are essentially cross-field devices. And finally, we will discuss traveling wave tubes or TWTs in short which are very popular microwave tubes.

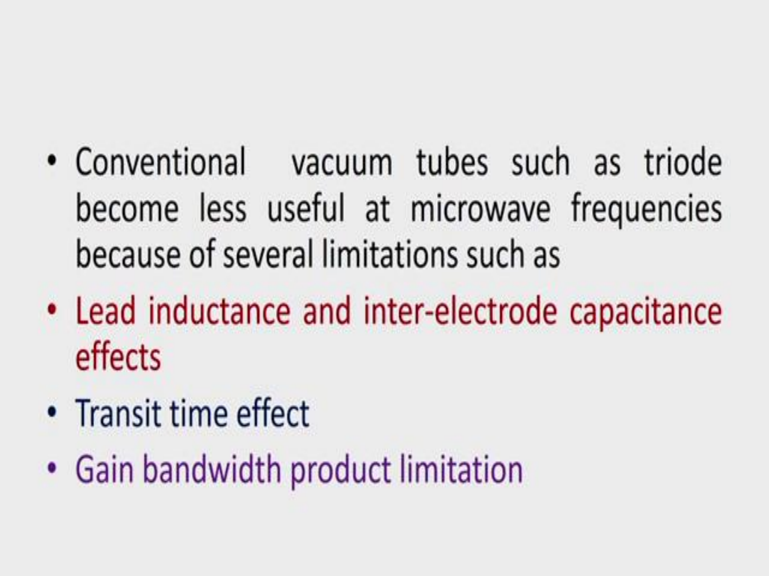
(Refer Slide Time: 2:35)



Microwave tubes are generally used for high power applications. Although solid state sources and amplifiers are becoming very popular in low power applications, for many applications, there is no alternative to microwave tubes, and tubes are very essential device for such systems. In fact, before the introduction of the solid-state devices which are capable of operating at microwave frequencies, tubes used to be the only device which provided amplification of signal, and also they were used as sources of microwave signal.

The scenario started changing after the introduction of solid-state microwave devices and gradually for the lower microwave frequency, and also particularly when the power requirement is not very high these devices became very preferable device. However, when it comes to high power applications where we require microwave power in the tune of kilowatts still microwave tubes are the predominant devices. And therefore, in this module we will briefly study some of the characteristics of these microwave tubes.

(Refer Slide Time: 4:55)



We begin our discussion by highlighting some of the limitations of the conventional tubes like triode, conventional vacuum tubes such as triode become less useful at microwave frequencies because of several limitations such as lead inductance and inter-electrode capacitance effect. So this parasitic inductance and capacitance often limit the operation of conventional tubes in the microwave frequency range.

Then another very important phenomenon is the transit time effect, and we will see later how in specialized microwave tubes this transit time effect is, in fact utilized. Gain bandwidth product limitations. So these are some of the limitations why conventional vacuum tubes could not be used effectively in the microwave frequency ranges, and we had to devise specialized tubes which are capable of operating in the microwave frequency range.

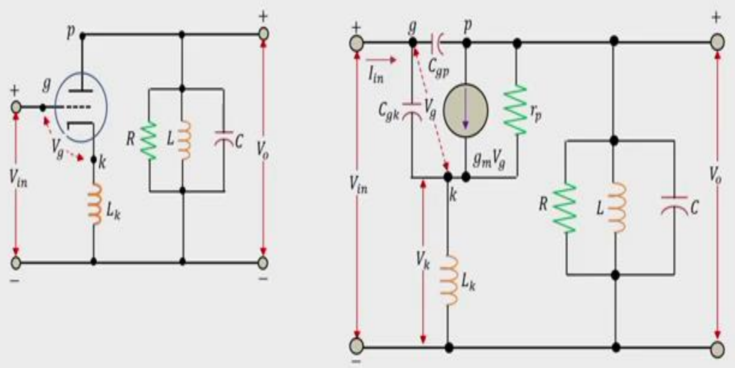
(Refer Slide Time: 6:50)

Parasitic reactances

- Above 1 GHz, parasitic reactances because of inter electrode capacitance and the lead inductance becomes very large
- Moreover, the real part of the input admittance becomes very large to cause overload of the input circuit thereby reducing the efficiency of the circuit.

So let us see the effect of parasitic reactances. Above 1 gigahertz, parasitic reactances because of inter-electrode capacitance, and the lead inductance becomes very large. Moreover, the real part of the input admittance becomes very large to cause overload of the input circuitry, thereby reducing the efficiency of the circuit.

(Refer Slide Time: 7:46)



Triode equivalent circuit taking into account the inter electrode capacitances and cathode inductance as the parasitic elements

Ref: S. M. Liao, Microwave devices and Circuits; 3/e, Prentice Hall of India, 2004.

So, we will try to understand these two effects with an example considering a conventional triode. So here we consider a triode which has a cathode which emits an electron and this anode which is maintained at a higher potential this potential difference between this cathode and anode accelerates the electrons, and finally they are collected at the anode, and this constitutes a current.

In triode, we have another terminal, which is called a grid through which these electrons can pass, and this grid is maintained at slightly higher potential as compared to cathode. And by controlling the voltage at the grid terminal the current flow between the anode and the cathode can be controlled. Now here, we are showing the voltage between this grid and cathode to be V_g and also the cathode terminal we are showing the parasitic inductance L_k.

Now, there will be capacitances between the grid and the cathode and also between the grid and the plate or anode. Now in this circuit, a resonant circuit RLC circuit, parallel RLC circuit is being connected between plate and cathode. So this is a load which can resonate. Now, if we consider the equivalent circuit of this triode between grid and cathode we have C_{gk}, which is the capacitance, parasitic capacitance formed between grid and cathode.

Similarly, between grid and plate, we have the capacitance C_{gp}, then between plate and cathode we have a current source gm V_g that means this current source voltage it is a dependent current source, the current value depends upon the voltage V_g and L_k as already mentioned is the parasitic inductance or stray inductance. And here we are showing this simplified equivalent circuit taking into account inter-electrode capacitances and cathode inductance as the parasitic elements. Now, this r P is the resistance between plate output resistance between plate and cathode usually will be very high.

(Refer Slide Time: 11:55)

$C_{gp} \ll C_{gk} \quad \omega L_k \ll \frac{1}{\omega C_{gk}}$

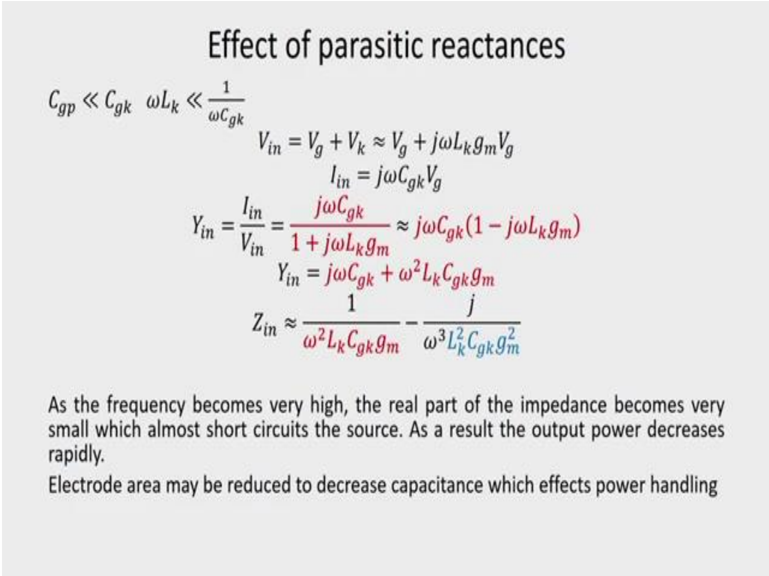
$$V_{in} = V_g + V_k \approx V_g + j\omega L_k g_m V_g$$

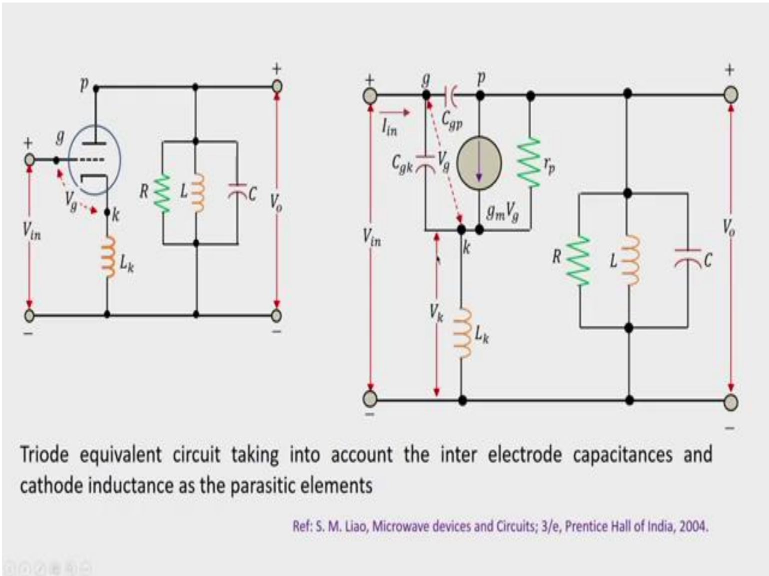
$$I_{in} = j\omega C_{gk} V_g$$

$$Y_{in} = \frac{I_{in}}{V_{in}} = \frac{j\omega C_{gk}}{1 + j\omega L_k g_m} \approx j\omega C_{gk}(1 - j\omega L_k g_m)$$

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

$$Z_{in} \approx \frac{1}{\omega^2 L_k C_{gk} g_m} - \frac{j}{\omega^3 L_k^2 C_{gk} g_m^2}$$





Now, if we analyze this circuit, we can write first of all C_{gp} the capacitance between gate and plate. This is much less compared to C_{gk}, the capacitance between grid and cathode. And also omega L_k the reactance provided by this parasitic inductance is much less compared to 1 by omega C gk. So these are true for practical vacuum tubes when operated at higher frequencies.

Now from this equivalent circuit we can see that V in is essentially V_g plus V_k, and this current since this is very small we have already mentioned r_p is very large, so essentially this current will flow through L_k. And therefore, we can write V in is equal to V_g plus V_k which is equal to Vg plus j omega L_k, and the current is gm V_g. Also, we have the input current I in as J omega C_{gk} V_g, this can be seen from the circuit here, I in is essentially the current flowing through this capacitor C_{gk}.

And therefore, now we can write Y in to be equal to I in by V in which becomes j Omega C_{gk} divided by 1 plus j omega L_k g_m, this V_g cancels from both numerator and denominator. Now, as we have said that this quantity will be small compared to 1. Therefore, we can write Y in to be approximately equal to j omega C_{gk} 1 minus j omega L_k g_m. And when this is expanded we get Y in is equal to j omega C_{gk} plus omega square L_k C_{gk} g_m.

Z_{in} is 1 by Y in, and when it is, when the expression for Z in is evaluated, we find Z_{in} equal to 1 by omega square L_k C_{gk} gm minus j by omega cube L_k square C_{gk} gm square. Now here, this real part of Z_{in} becomes very small at higher frequencies, that means when we try to operate the tube in the microwave frequency range and as the frequency becomes very high the real part of the impedance becomes very small, which almost short-circuits the source.

And when this happens, as a result, the output power decreases rapidly, so we find that the effect of this parasitic inductance and capacitance is that they actually reduce the power at the output of the tube as the real part of the input impedance become very very small and signal given at the input instead of being amplified it gets short-circuited to the ground. If we reduce the electrode area, then the capacitance can be decreased. But then, this will also result in lowering the power handling capacity of this type of device.

(Refer Slide Time: 17:53)

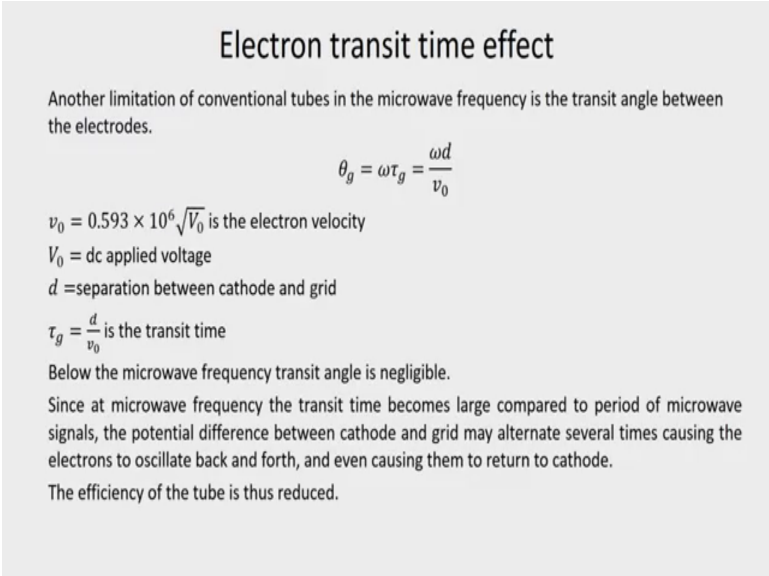
$$\theta_g = \omega\tau_g = \frac{\omega d}{v_0}$$

$v_0 = 0.593 \times 10^6\sqrt{V_0}$ is the electron velocity

$V_0 =$ dc applied voltage

$d =$separation between cathode and grid

$\tau_g = \frac{d}{v_0}$ is the transit time



Another important effect which is required to be considered is the electron transit time effect. Now, when these electrons they are emitted from the cathode, and they are accelerated by the field present between cathode and anode, the electrons take finite time to reach the anode, and we will see that this comes as a limitation in operating the conventional tubes at very high frequencies like microwave frequencies.

Now, we denote it in terms of transit angle theta g which is omega the angular frequency into tau g, the transit time of the electrons and this can be written as omega d by v naught, where v naught is the velocity of the electrons, and this depends upon the applied dc voltage capital V naught and d is the separation between the cathode and the grid. And tau g is the transit time between the cathode and the grid.

Now, below microwave frequency, this transit time of the electrons is negligible. But, at microwave frequency the transit time becomes large compared to the period of microwave signals. As we have already mentioned we intend to use this device, the triode, as an amplifier. And we apply the AC signal at the grid.

Now, at microwave frequencies, as the time period becomes very, very small this electron transit time between the cathode and the grid it becomes much larger compared to the transit time of the electrons. And if this is the scenario the potential difference between the cathode and the grid may alternate several times during this electron transit time and causing the electrons to oscillate back and forth. Because when the grid is positive with respect to the cathode it accelerates the electrons; it supplies energy. But when the grid goes to negative, it becomes, it actually deaccelerates the electron, and it takes away energy.

So we have a scenario before the electron can cross the grid, the potential being changing several times, and this may cause the electron to oscillate back and forth and even causing some of the electrons to return to the cathode. And when this happens, the efficiency of the tube is reduced. So we find that the parasitic reactances and also the transit time affect the efficiency of the tube.

In fact, if we attempt to reduce the spacing between the grid and the cathode to reduce the transit time, this will enhance the capacitance. And therefore, we find that the design requirements are actually contradictory.