Basic Building Blocks of Microwave Engineering
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Lecture – 17
Microwave Tubes: Part I

Welcome to this 17th lecture of this course on basic building blocks of microwave engineering. Now, in this in we will see the signal microwave signal how it is produced.

Now microwave signal can be if it is a low power signal that can be produced by solid state devices, but if it is high powered then solid state devices they cannot produce high power. So, generally if you want give someone or 2 watt power that also solid state devices generally cannot produce that. So, we take the help of tubes to produce, but microwave tubes are use a there is a problem to use the conventional tubes like the diode vacuum tube, triode pentode which are used for producing low frequency signals. Historically before solid state thing came they were the primary source of power, in all previous radio receivers, radio transmitters, we used to have this vacuum tubes diode triode pentode etcetera. But in microwave region; that means, in more than one gigahertz they cannot be used their principle of operation prohibits the use of them we will discuss that.

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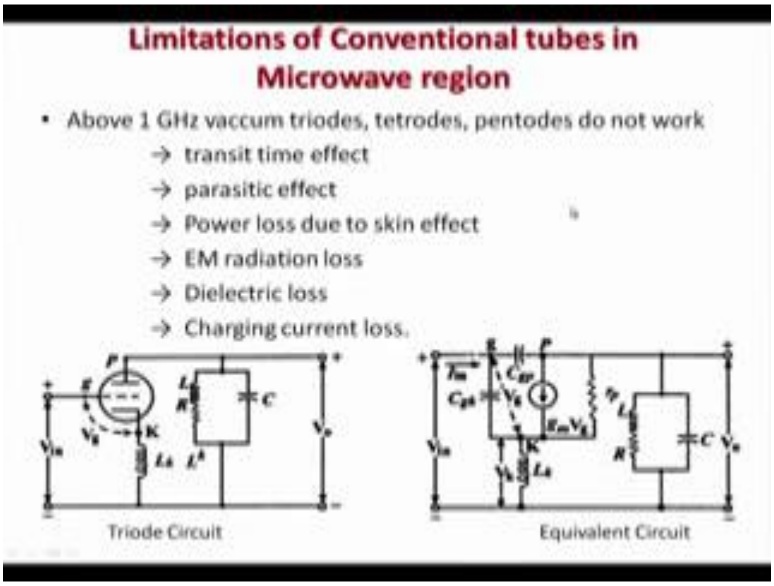

So, let us see that what is the limitation of conventional tubes in microwave region.

Above one gigahertz, this vacuum triodes tetrodes pentodes they do not work; this is a typical triode circuit. The cathode the plate the grid this is a equivalence circuit for that.

So, why they do not work, because one effect called transit time effect; we will discuss that there is another effect called parasitic effect. That at high frequency the lead inductance and capacitance there we know that inductance and capacitance they are functions of frequency. So, high frequency the inductance increases. So, the reactance also increases where as in capacitance that increases. So, the reactance that becomes lower and lower.

So, that is parasitic effect that also effects the operation. Then we know that if we go higher in frequency, there is a problem that should the power cannot penetrate much, but it penetrates some up to skin depth of a conductor. So, there are conductors everywhere in the diode or in the vacuum tubes etcetera. So, some power is loss, that we calculated the conductor loss when we calculated in coaxial line, or web guides etcetera. So, we have seen that due to that skin effect the diffusion of diffusion, current that flows in the penetration direction that gives rise to power loss. So, power loss increases, then also at higher frequency more and more radiation takes place. So, all these tubes etcetera their signals they will start radiating through that will give to some loss, because we do not want a radiation here from a signal source.

Similarly, we have discussed that there are dielectrics also in the various things. So, the dielectric loss is there. Also higher frequency the junction capacitance of various tubes they increase. Now any capacitance means you need to charge that in the transient time. So, that also some power is needed to charge that. So, those, but out of this six; obviously, these are where we take, but these 2 are most fundamental the first 2 effects which limits the limitations.

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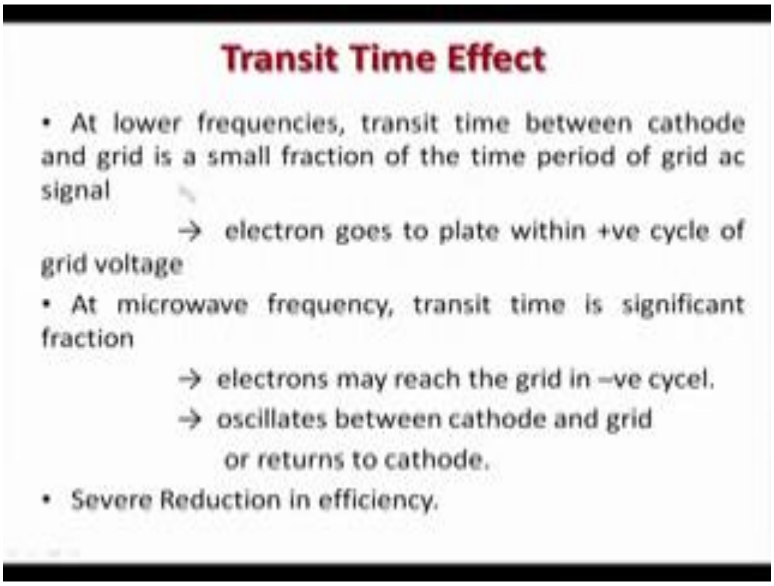

So, that is why we will discuss them in a bit more detail. Transit time effect what is transit time effect. At lower frequencies transit time between cathode and grid is a small fraction of the time period of the creative signal

You see that electrons we know the operation of this. So, when this is the cathode. When the cathode is heated then from some electrons, they are emitted they pass this grid and gets collected to the plate. Now when they come to the grid, now grid should further send them towards the plate. So, this means that if suppose the when the electron was emitted that time the cathode voltage was that time the sorry AC voltage, that is coming into the grid that was positive. So, it will come. And if still the grid is positive then it will send it here, but if the frequencies says that by the time the electron came here, that time the grid has changed it is polarity; that means, when it was emitted grid was positive it was seen that, but when it came grid becomes positive. Then the electron will be repelled because positive grid means that will repel the electrons. So, it will not act like the electrons and electron cannot go there.

So, transit time means, here the transit time between the time taken by an electron to go from this cathode to the grid. Now, that should be a small fraction of the time period of grid AC signal, so grid as an AC signal. So, within a fraction of this; that means, within this positive cycle within one fraction, the electron should transit from plate to the grid, but what happens when we increase high frequency high. That time the due to the short transit time the electron short time not short time, due to the very high frequency the grid is changing it is polarity very fast. So, by the time electron is coming from the cathode to the grid the grid has changed it is polarity. So, electron goes to plate within positive this is called forward frequency, but at microwave frequency the transit time becomes a significant fraction. Even it can become some integral or some integral multiple of the cycle etcetera. So, electrons may reach the grid in negative cycle.

And if that happens then electrons will be coming back. Again you will try to send again the cathode will try to send them. And they will reach the grid and again the same thing will happen. So, the electrons will be oscillating between the cathode and grid. Or there may be that they are returning to grid they are no more going to the higher they give their energy there. So, the basic purpose of a any source that the electron should reach the plate that is stopped or that is severely impaired if we go to higher frequency where the grid signal is very fast changing and. So, we cannot do that. So, severe reduction in efficiency of the circuit takes efficiency of the tube takes place due to the transit time effect ok.

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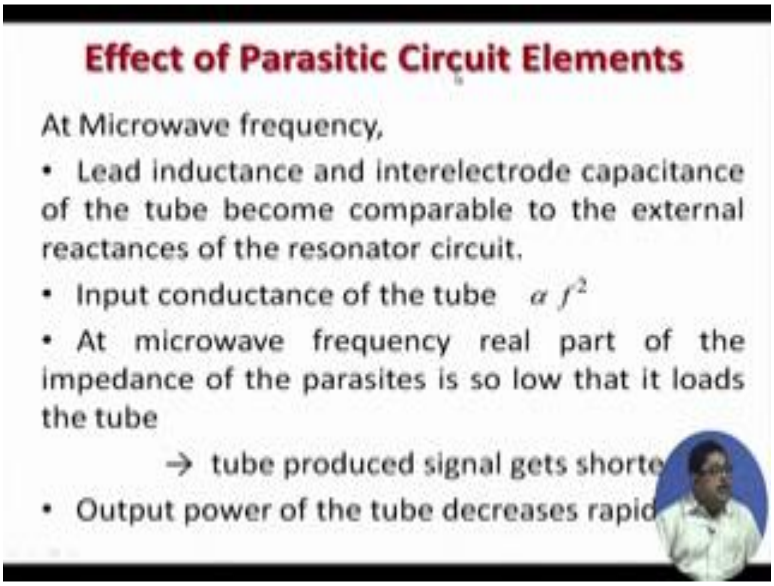

Now, what is parasitic effect? That at microwave frequency lead inductance and interelectrode capacitance of the tube becomes comparable to the external reactances of the resonator circuit. You see always with a any source any vacuum source or any solid state source, they cannot produce very high power, but we require an LC circuit as to we have seen in resonator classes, that this LC circuits these are still that oscillation, they amplify that oscillation and send. Now if at high frequency the lead inductance all these are leads there are outside is connected to leads, then there are this gaps they produce capacitance, now at high frequency these values if they become comparable to this l and c values, of the external r c circuit comparable to the external reactances of the resonator circuit.

Now input conductance of the tube if we calculate, that is a function of f square. So, as we go higher and higher in frequency, it go input conductance increases very fast. Now conductance means what input conductance means g. So, at microwave frequency we can say the resistance part or real part of the impedance that is resistance of the parasites that is becoming very low. So, that they load the tube. So, resistance is very low. So, the signal that is being produced by the signal, that is seeing in the external circuitry lead and others they are getting a short circuit path. Low resistance means that short path. So, instead of producing going to the plate etcetera; they will try to be whatever electrons are getting generated they will try to go to the lead and get them. So, output power of the tube decreases happily due to this because tube produced signal they get shorted by those path. So, instead of going to the resonant circuit, they try to go to the lead inductance and a.

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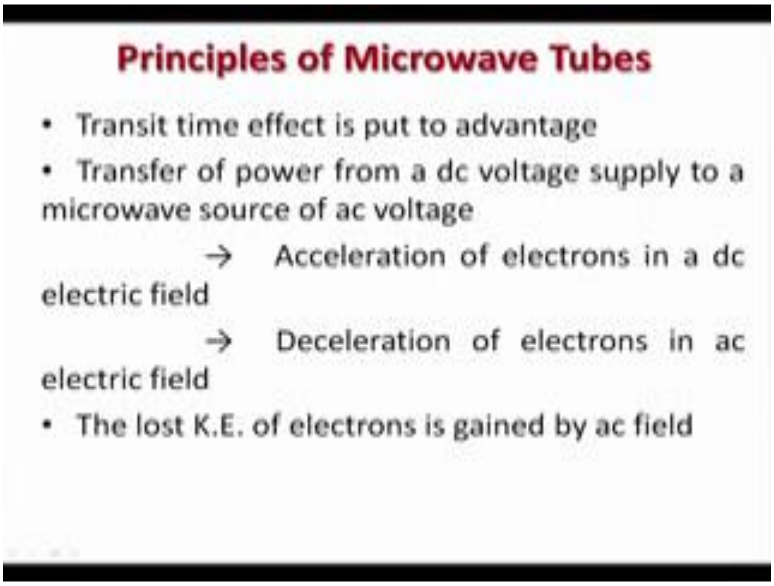

So, we need to then, take a new principles of microwave tubes, now what. So, we see the transit time is a is a impairment in case of low frequency tubes, but then people thought that let us use this transit time in a more intelligent way. So, the whole tube things were done and those are microwave tubes here transit time effect is put to advantage. So, what happens here a power from a DC voltage, a DC voltage creates some electrons and in that high DC voltage the electrons they are sent. So, there is an electron beam produces acceleration of electrons in a DC electric field is produced and then this there is an AC electric field produced where that deceleration of electrons takes place.

So, the DC voltage has given some energy that is why the electrons were accelerating now if I can decelerate that by some means that we will see there also we will see that cavity is the thing cavity resonator that decelerates that and if I decelerate that. So, they lose the energy so, but total energy cannot go. So, the electrons they lose kinetic energy. So, they transfer that energy to the AC field or the cavity field. So, to the cavity they give their energy because cavity is the system which is decelerating them. So, they give the energy to the cavity takes it and give it to the microwave signal and microwave signal goes on taking it is increasing it is energy; that means, it is power etcetera goes. So, then from the cavity that microwave signal is established.

So, the loss kinetic energy of electrons is gained by AC field. All the microwave tubes are based on this principle. Now how you this acceleration of electrons is easy in all the low frequency tubes also this takes place, but this deceleration is a clever thing. It is done very cleverly that these electrons there are then decelerated by some separate arrangement. And that we will see that how that is done. That also from the basic principles of microwave engineering what we have already covered from that we will try to see that how that is done. Now different microwave tubes that we differently that is why there are several tubes there.

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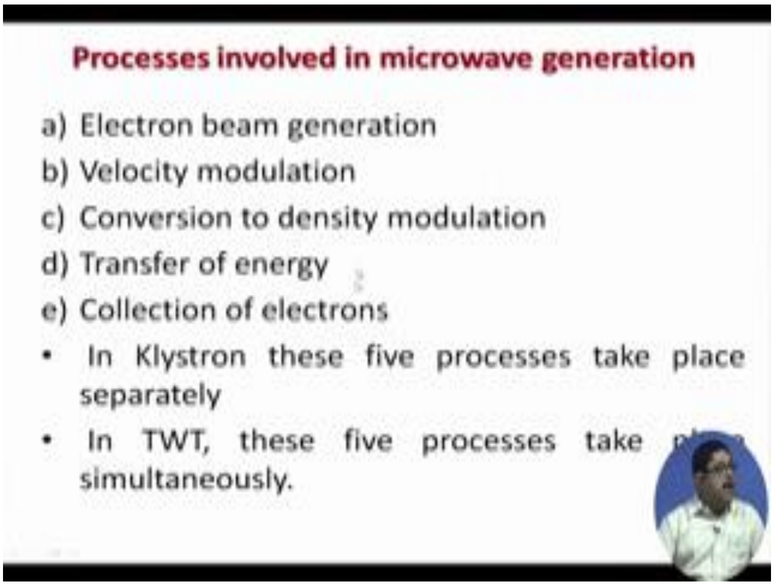

But all of them will do this and. So, the processes involved in microwave generation there are 5 processes which all the tubes do. So, the first is you have already guessed that it is electron beam you will have to generate. So, there should be an electron gun which generates electron beam.

Now, this is the new thing. There is a term called velocity modulation we will see that that various electrons their velocities changed. So, that there is a think on velocity modulation and that velocity modulation is put to use by converting that to density modulation. So, in the space in a finite space that various electron there is a electron density that changes. So, even if the when the electron was produced every space, was having same electron density, but due to velocity modulation the space gets different density of electrons that is called density modulation. So, when that takes place then then they will see that due to this density modulation the electrons get decelerated. So, they will lose some part of their kinetic energy. And that kinetic energy they transferred. That energy should be taken to the cavity and the electrons those which are decelerated they finally, need to be collected because otherwise the whole circuit cannot complete.

So, now this high processes in some tubes they take place separately in some tubes they takes place simultaneously. So, if they take place simultaneously it is difficult to understand them, but people have made some other ways to understand them. So, traveling wave tube is an example where these 5 processes take place simultaneously.

Whereas the klystron, in a klystron tube these 5 processes takes place separately. That is why we will first see the klystron because if it is separate processes it is easy to understand that what is happening where.

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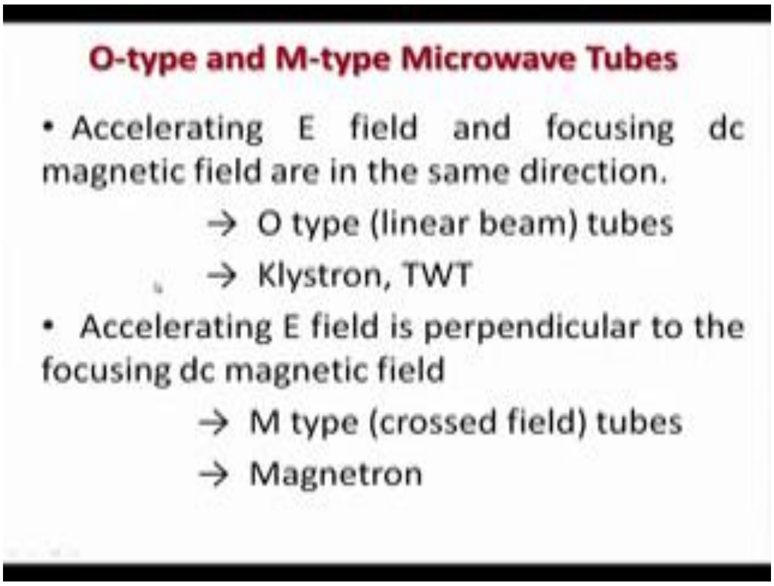

Now, there is also classification of microwave tubes in terms of time. Basically 2 types of tubes are there o type and m type. Now o type means o types are also called linear beam tubes o type means the accelerating e field and the electrons will be when that a velocity modulated that time they need to be focused. So, that they do not go away from a particular region because otherwise we will lose some electrons. So, we will not be able to extract energy for that. So, there is a focusing DC magnetic field needed.

Now, if accelerating e field and focusing DC magnetic field are in the same direction then it is called o type or linear beam tubes. The examples are klystron TWT. Here you see klystron and TWT they are of same thing. It is as we saw that there those 5 processes are different and simultaneous that is one thing, but here both of them have the accelerating e field and focusing DC magnetic field in the same direction that is why they are called o type tubes. Similarly if the these 2 fields accelerating electric field and focusing DC magnetic field are perpendicular then that is called m type tubes. One example is magnetron.

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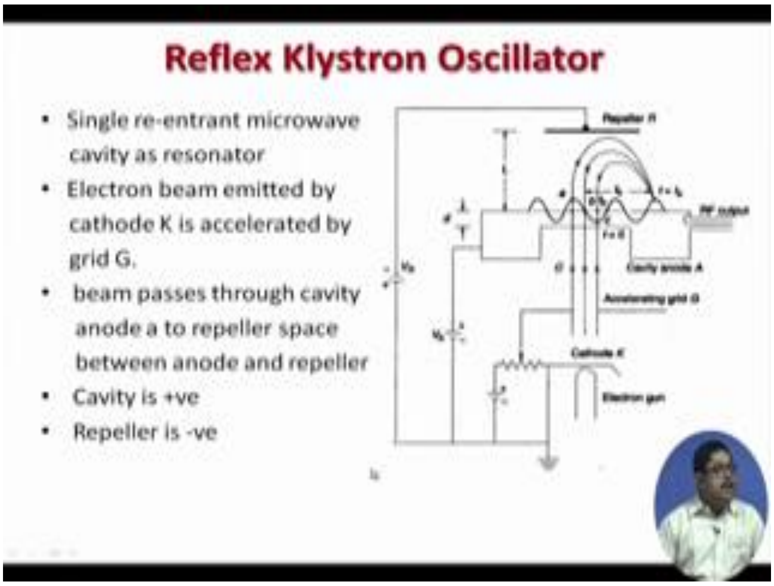

So, first see the klystron oscillator. It is also called reflex klystron oscillator. Now you see the heart of this is there is a cavity. You see the cavity this is the cavity up to here then there is a loose portion of the cavity. Then again there is a cavity this type of structure is called re-entrant cavity. You have one cavity actually instead of the whole thing becoming a cavity resonator you have some portion where you leap, but since electrons are flowing near they will start going through these space and then again you have a resonator this is called re-entrant structure that is why the name re-entrant microwave cavity.

So, you have a single re-entrant cavity. So, re-entrant cavity will have these 2 parts that it is broken in it has to this components and there is a internal space. Where the cavity is continuing this space is small then you have another cavity. Now here you see that there is an electron gun so; that means, a cathode is there and; obviously, that electron in the cathode is being electron gun is producing the energy these are generally some high voltage battery is there. So, our power supply is there. So, electron is produced now. There is cathode and anode. So, you see the this cathode is here then there is a grid which is having positive with respect to the cathode is negative and where is the anode you see the anode is here. So, the cavity is made as anode. So, this whole cavity we are calling cavity anode. Because it is connected by this positive supply, and also there is another electrode that is called repeller electrode r.

Now, repeller electrode is negative with respect to the anode. So, anode; that means this cavity this is full metallic cavity so; that means, the whole structure is positive that is why it is anode, but there is a negative electrode called repeller within some distance at a distance l from the anode. This space between repeller and anode this is called repeller space. Now as usual electron beam emitted by cathode k is accelerated by grid g this is the acceleration grid g. So, they go more towards the plate or more towards the anode. Now the beam passes you see that since there is no metal plates here n. The reentrant cavity this space is kept without any metal exists where the solid line is there. So, the electrons now they come to the anode now there is no plate created here to collect them there is no collector here. So, they go on they go on through this space, but when they come here then they are under the influence of this repeller. So, it is having a negative voltage. So, they get start getting retarded. So, due to their motion they will come here.

Now, what happens the cavity is positive repeller is negative and these distance; that means, the gap this gap is of a distance d; that means, the re-entrant cavity is this gap this is d and now another thing you see we are showing a AC signal where from that AC signal came because this is DC field actually that this is a resonant cavity. So, it has a resonating frequency. Now this anode it has a DC field. Anode it is a positive field what happens this produces some noise, any DC field any electric filed there is some noise. So, this DC field has some noise. Now since it is a resonating structure depending on how we designed it is resonant frequency value, one AC signal and generally it is a microwave resonator. So, it is resonance frequency is in the microwave region. So, from the DC field it gets a microwave signal. So, there is already some microwave AC signal that is shown here. At microwave frequency; that means, more than some gigahertz signal is there it is an AC signal. So, you have this AC signal.

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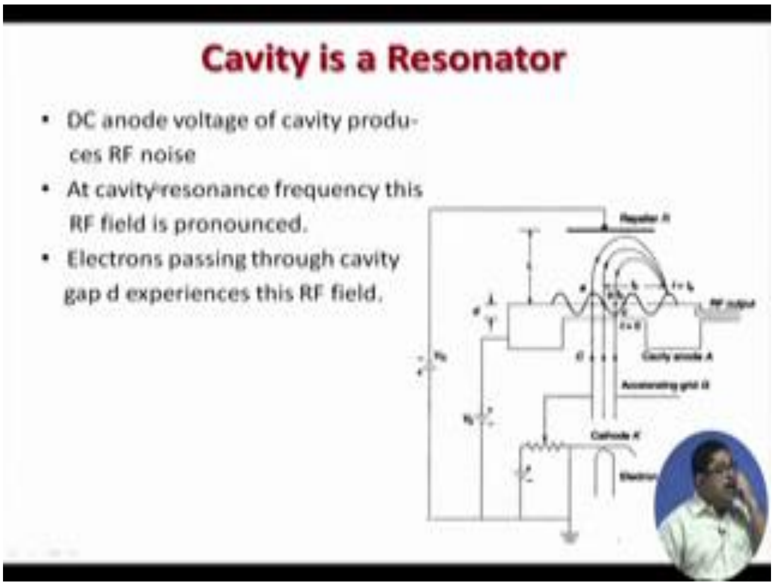

Now, can we; what I said DC anode voltage of cavity produces RF noise. At cavity resonance frequency this RF field is pronounced that I said. So, electrons passing through cavity gap d experience this RF field. Now this is the clever way by which the velocity modulation is produced.

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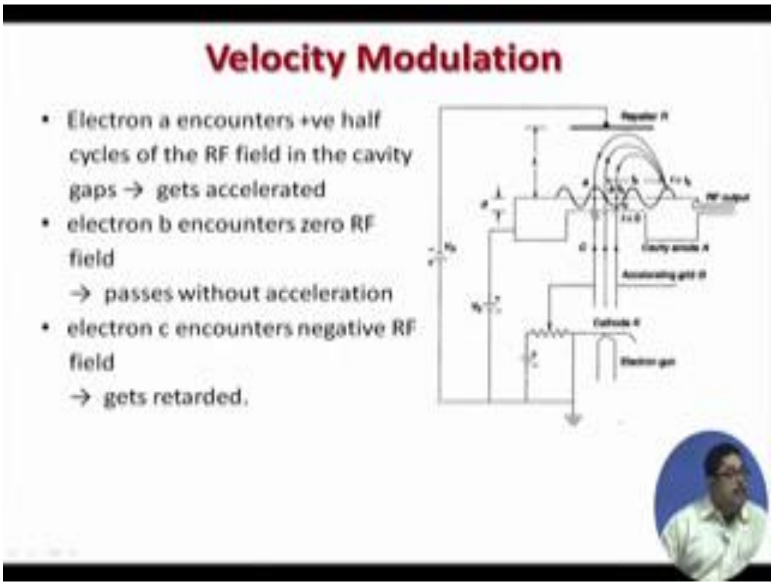

What happens we have noted here that? Let us consider 3 phase of this RF field one is a, is do not confuse it with cavity anode a. This is positive a sorry capital a, but this is our small a, that RF field when it is at the peak then there is b. B is this when RF field is going to 0. And c is when RF field is gone to the negative peak, a b c are 3 points. So, let us consider an electron which has come and saw this filed in the cavity gap d. Electron a encounter's positive half cycles of the RF field in the cavity gap. So, this is peak, but if the voltage is positive, it will be an electron. So, it will be further accelerated. So, this also is the at point a it gets huge acceleration maximum acceleration possible it goes, but when it goes near repeller it will get accelerated. So, it is trajectory will be like this, if we do the simple mechanics it will be like this.

Now, let us see electron b. Electron b does not see any RF field RF filed is 0 there. So, with whatever velocity it was coming there is no acceleration it goes then it sees the repeller negative voltage it is trajectory will be like this, and electron c that sees a negative RF field. So, it will be it gets retarded and further when it enters into the repeller space it will be it is trajectory. Now this repeller voltage and this l the repeller space distance that is the actual design that is created such that, all these 3 extremes a b c they are retarded, but they are when they should their trajectory will meet at a point. So, if that is done as this is shown. That is called bunching of electron this is the density modulation. That at a particular place here they bunch.

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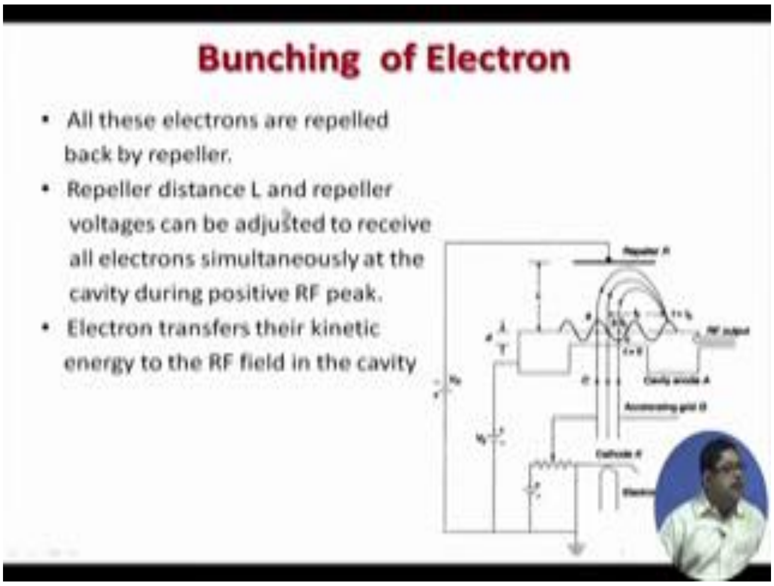

Now, here you see they are cleverly made to meet at the point where the next rth cycle peak is coming. So, all these electrons are repelled back by repeller, repeller distance l, and repeller voltages can be adjusted to receive all electrons simultaneously at the cavity during positive RF peak. If that is there then RF signal has the maximum power at it is peak, but these electrons are bunched they are getting retarded because this is the retarding path. So, they have lost the energy, so where they will give that energy. They see now one person there is an RF field.

So, they give that energy to the RF field. RF field also once you take that energy it takes that energy. So, all electrons are received by the RF field simultaneously this is the density modulation and from the bunch this is called bunching of electrons. So, from the bunching of different velocity electrons different acceleration phasing electrons they are bunching at a point and from that point the RF field they encounter. So, RF field takes that energy. Electron transfer their kinetic energy to the RF filed in the cavity.

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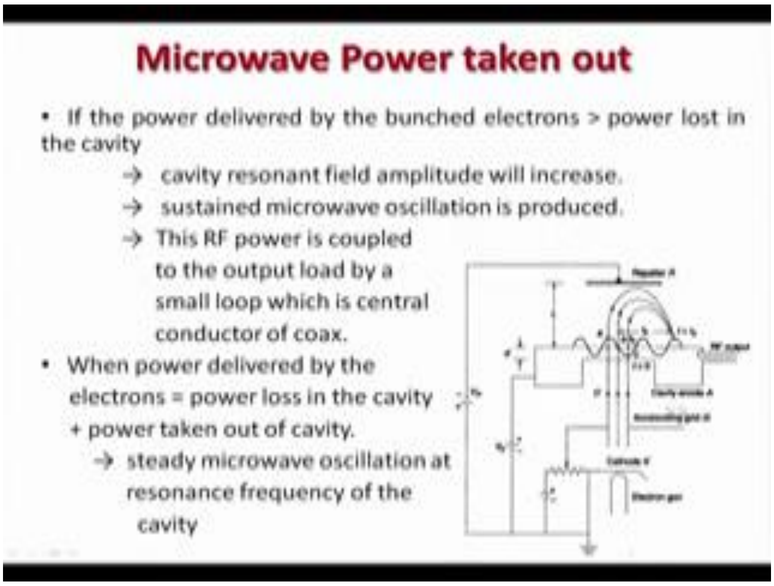

So, if the now from the, so, the cavities field is increasing and. So, it is gradually it is energy is increasing; obviously, in the cavity there is some loss, but if by bunching and by electron transfer electrons can transfer or make up for that loss, that is taking place in the cavity. Then cavity resonant field amplitude will go on increase gradually. At one point of time the transfer of energy and that loss is same that time it will be a sustained oscillation. Sustained microwave oscillation is produced this RF power can be extracted you see there is a loop coupled here, coaxial line it is centre conducted you see that is in the form of loop it is put any loop it can extract power it is basically an antenna. So, it can take that power and this RF output is taken to a load where you or it is opened. So, the in the open end you can give that power. So, tubes you can extract power from there which is central conductor of coax. When power delivered by the electrons is equal to power loss in the cavity plus power taken out of the cavity when these 2 are equal steady microwave oscillation at resonance frequency of the cavity.

So, I repeat once again that there is electrons the grid is accelerating their energy, so giving more energy. Then they are entering the re-entrant cavity they are depending on the RF field already they are, they are seeing some RF field where from this RF field came from the noise that was RF noise that was produced by the biasing anode voltage. So, from that, but this is a resonator. So, already it has resonated there and that resonant microwave frequency. So, there is a RF field now different electrons and seeing the different RF field. Then when they are going to the repeller space they are seeing the repeller voltage.

So, all of them are getting retarded, but since their energy with them or velocity with them is different, they will have different trajectories. Now that clever engineering design is you will have to collect them at a point. And that point also should lie on the RF signals peak. So, it can meet here. All otherwise we will design it that it can meet at the next RF cycle peak or next RF cycle peak, but those electrons which are coming in between if they are not in the peak. Then RF unnecessary because RF signal we want that at it is maximum power the power should again increase. Then again increase, but if it is at other power then the maximum extraction is not possible. So, it is designed. So, that only at RF cycle power it will be there.

We know what is the cavity is our design. So, cavity we know that what will be this frequency. So, we will make this bunching. So, that it takes place only at the peak.

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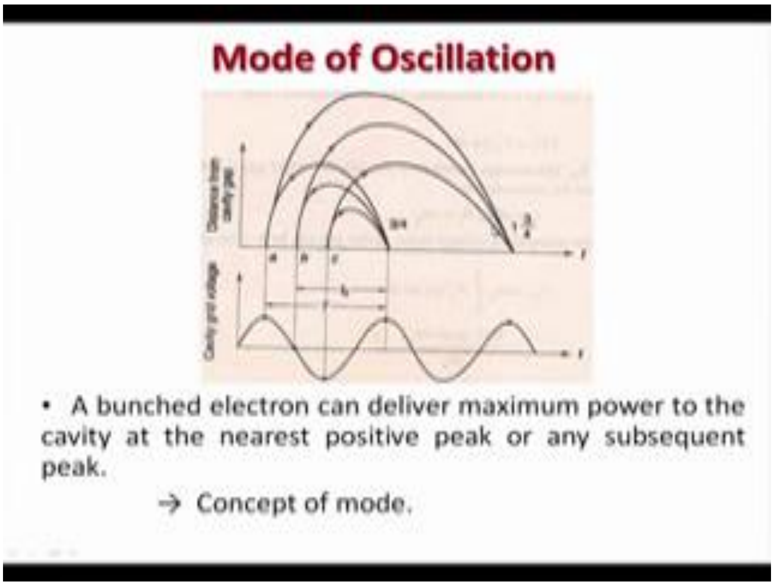

So, this is the, now what I said that the bunching may takes place here. Or bunching may takes place at the next RF cycle peak or next peak; obviously, the. So, different bunching now this bunched electron can deliver maximum power to the cavity, at the nearest positive peak or any subsequent peak. Now where you are collecting whether in when a electron is passing whether here it is giving the energy, or here it is giving the energy or there it is giving the energy. So, there are various modes of oscillation. So, this is the concept of mode that whether in the next one, it is giving or to the next one or to the next one. So, there will be various modes because these are this node is not energy delivered at all the places at some discrete places. So, there will be some discrete modes.

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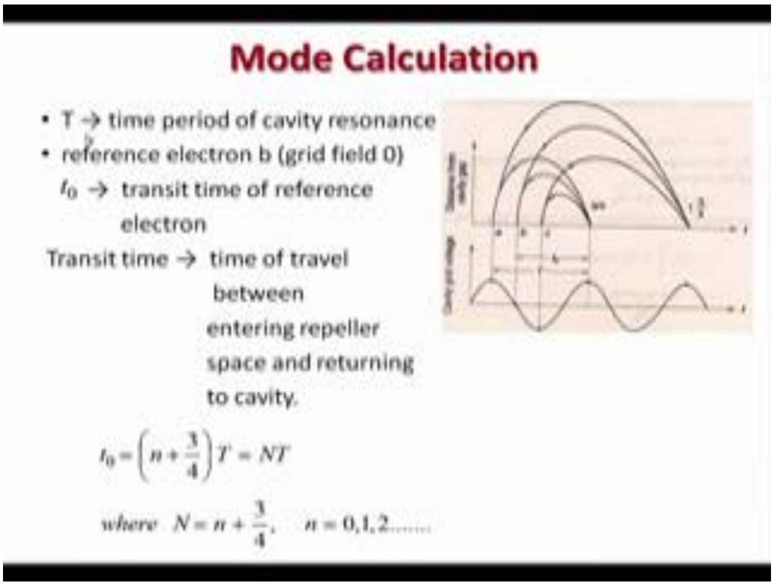

Now, to calculate that mode, if time period of cavity resonance; that means, the microwave signal frequency of that is t, then you consider the reference electron b. It encountered the RF field at field 0. And the t 0 is the transit time of reference electron. Transit time means time of travel between entering repeller space and returning to cavity; that means, it has entered here you see. So, the time it took to go from here to here or time it took from go to here to here. So, it has in this mode; that means if this bunching this is it is the time taken by it to cover this trajectory, or the time taken by it to cover this trajectory, or the time taken by it to cover another trajectory etcetera. So, t 0 we can say that you see that when it is entering so; that means, from here to here, what is this if this is total t then what is the time when from 0 to the next peak. So, it has full half cycle then a quarter cycles; that means 3 t by 4. So, that we are saying that t 0 is equal to n t plus c t by 4. And that we are giving n plus 3 by 4. That we are saying is a number capital number n; obviously, n is not necessary not an integer, but small n is an integer capital n is not an integer, but small n is an integer, but n is the number of mode. So, mode designation is capital n. So, what will be there; that means there will be.

When n small n is 0, there will be 3 by 4 modes; when small n is one there will be one 3 by 4 mode. Then there are 2 3 by 4 mode etcetera. So, this equation is satisfied by this solution is non-unique there are various possibilities. As we have seen modes of the signal similarly here this electron it will be delivering power. So, there will be that bunching thing. Here will be various modes of operation modes of oscillation. So, at various modes we will get various powers.

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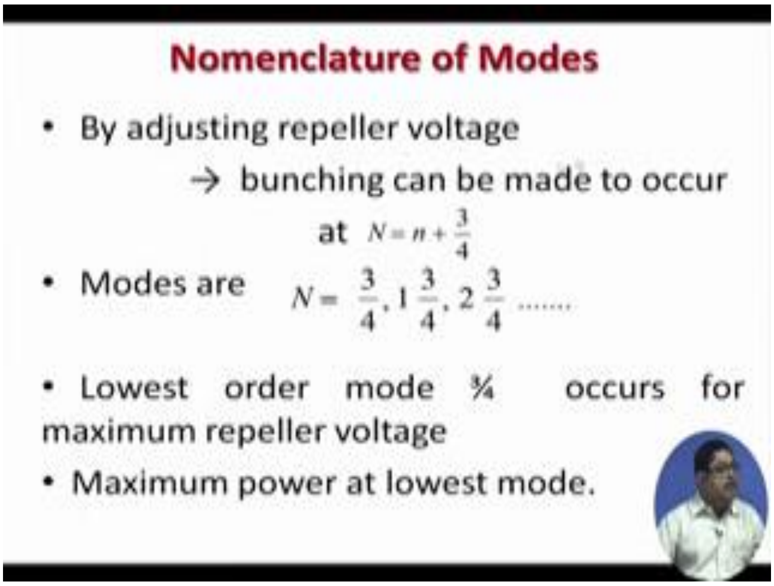

So, by adjusting people are voltage bunching can be made to occur at n, is equal to n plus 3 by four. So, who is creating that, you see who is responsible for whether the electron will go here or go here, that is dependent on the repeller voltage. So, repeller voltage if I make very high repeller is negative. So, it is very high. So, the bunching will be taking place very near; that means, the first bunching if I made it something less negative then it will go to next. If I make it further less or negative it will go to here. So, repeller voltage determines which mode will be there.

So, modes are this the first mode is 3 by 4 etcetera; obviously, the lowest order mode will occur for maximum repeller voltage and; obviously, most of the if I make the repeller voltage very high then maximum power because most of the electrons there will be force to deliver their energy. So, power also is highest at lowest mode, but theoretically this is calculated. Actually it is very difficult to have these 3 by 4 modes. So, generally in practice we get one 3 by 4 2 3 by 4 etcetera mode it is very that type of high repeller voltage required also that bunching in such a short rate does not takes place, but theoretically this mode is possible. Practically it is difficult to get this mode. So, it is the lowest mode.

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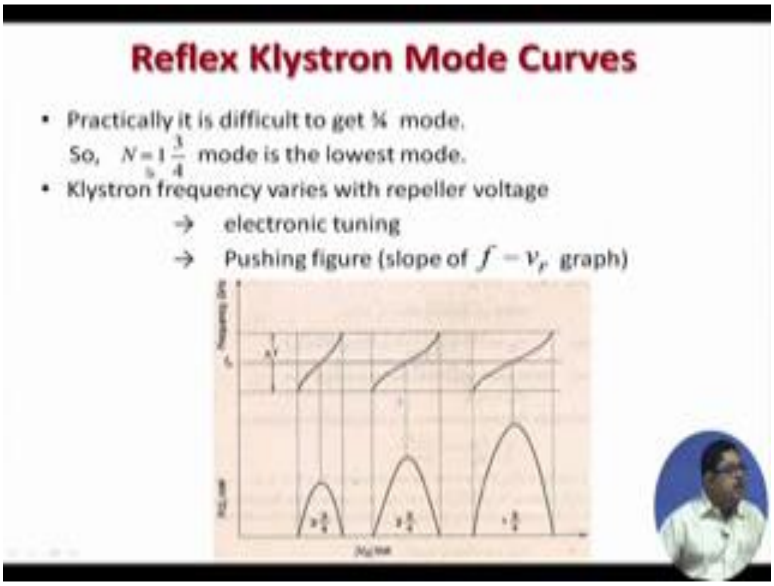

So, we make in our laboratory microwave laboratory, we make the people we give them a klystron and then ask to plot this mode. Because at the mode the maximum power. So, current will be different. So, they find out what is the current at various repeller voltages. So, you plot various repeller voltages, and you plot what is the microwave power. So, by power meter they can make it, or by in v s w r meter also they can see. So, by power meter if you see for this power output what is it is repeller voltage it will be like this is v r magnitude the repeller voltage magnitude; obviously, always repeller voltage is positive. So, you see the lowest mode one 3 by 4 practical lowest mode, there you get maximum current, then no current, but in between you see there is a from here from here to here there is lot of space where no current is there.

That is true because if I go on changing the repeller voltage suppose I am reducing the repeller voltage magnitude, but always the bunching on takes place bunching will take place only at regular intervals. So, that is why in between there are no modes. No, no current power output. So, this and klystron frequency also that will vary with the repeller voltage as we said that if you do that, the frequency of the thing because the klystron frequency is this if I change the repeller voltage here, then the energy of extraction on the period is changing. So, if we plot the frequency output versus the repeller voltage then we get this type of thing.

This shows that, we can electronically tune the klystron also. That means, you change the repeller voltage, there is you can tune. So, how much electronically you can tune; obviously, this is not much. So, that is given by slope of this f by v r curve. Del v by del v r that is the pushing figure we call. So, pushing figure of a klystron is the slope of this. So, if I am here at this repeller voltage I will get some slope. So, it depends on v r what is the value, but it can be calculated. So, that is the beauty of this electronic tuning, but in a klystron.

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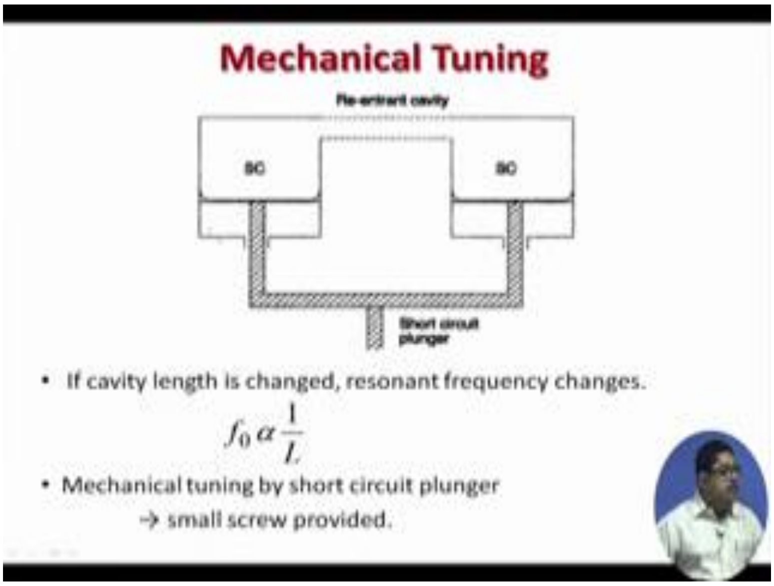

There is also a mechanical tuning possible. That is you see that you can say resonator. So, the re-entrant cavity, if I change the cavity s dimension then also the frequency will change. So, if cavity length is changed resonant frequency changes. So, that klystron frequency will change. Also we have seen electronic tuning that electronic tuning by changing the repeller voltage you are changing where they are extracting power. So, it is frequency will also change. So, mechanical tuning is by there is a short circuit plunger is there. So, you will have to do it symmetrically because re-entrant cavity means 2 parts of this re-entrant cavity there should be of equal depth. So, you should have a short circuit plunger. If you move it this is moving the cavity dimension and. So, cavity length is changed. The out frequency is one by l. So, if you make it shorter you get higher frequency.

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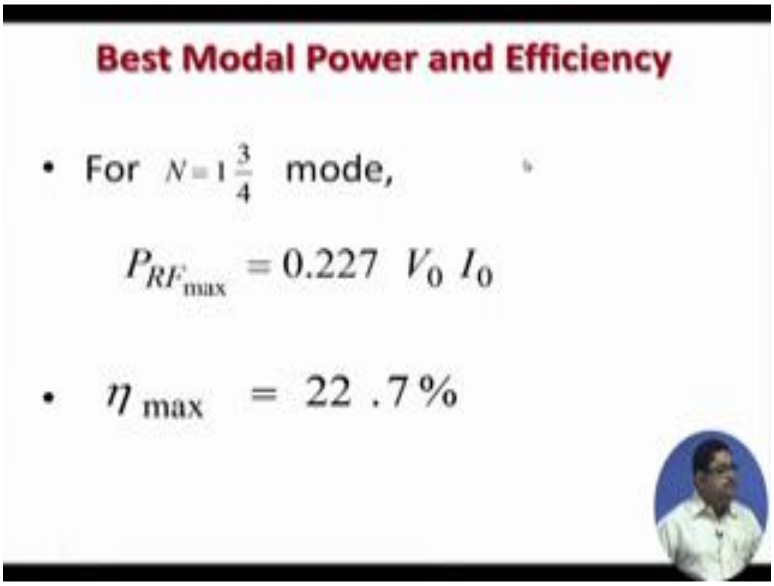

So, best modal power and efficiency n is equal to one by 3 4 mode. You can get the power the expression is if you do the mathematics of klystron. I have avoided that, but you should know that it is then v naught I naught. These are the plate voltages and current and maximum efficiency from reflex slide shown you can get 22.7 it is called reflex because you are making the electron to go and then again it is coming back that trajectory that is called reflex, because it is changing the reflection taking place. Reflection not our normal wave reflection r e basically reflects change of path or change of slope that is called reflex r e f l e x.

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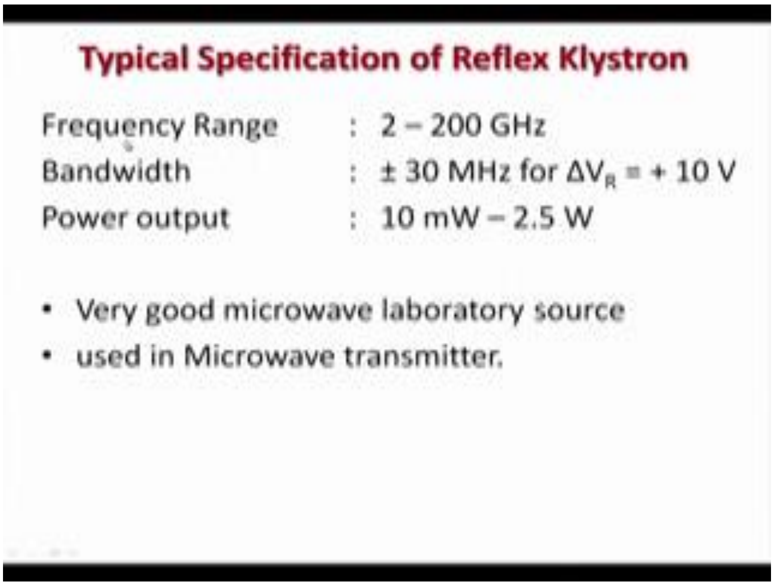

Typical specification of reflex klystron and frequency range, you can go from 2 to 2 hundred gigahertz. In our lab we have an x band one which can go from 8 to 12 gigahertz. Bandwidth is typically some megahertz. So, you say it is a narrow band device for a particular change of repeller voltage you can; that means, delta v r of if you change the repeller voltage by 10 volt, you can change the frequency of operation by 30 megahertz power output 10 milliwatt to 2.5 watt. So, say from some milliwatt to several watts, reflex klystron, give high power reflex klystron, is a different ball game. That is called relativistic klystron.

Nowadays people are researching on that. That how to create gigawatts of power from klystron, but this reflex klystron is a small energy or small power klystron; it is a very good microwave laboratory source, very stable you can use those modes etcetera the modes are traceable, because it is a very stable source and used in also in microwave low power transmitters, and this reflex klystron is heavily used.

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This is the picture of a reflex klystron, you see that this whole mounting thing is put and this; this is the mechanical screw that short plunger. So, this screw if you tune then you can change the frequency of the klystron this is the mechanical tuning, and by repelling or a repeller voltage change also you can change it down. Point is if you in the lab you should do it, but when the klystron has operated for certain time it becomes hot. So, please at least use a handkerchief. I always use a handkerchief to tune the change that because otherwise you may get a thermal shock.

Thank you this is all about reflex klystron.