Millimeter Wave Technology.
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Lecture-09.
Guiding Structures (Contd.)

So we have seen that alpha C and alpha D the attenuation constants they are function of frequency or any given guiding structure.

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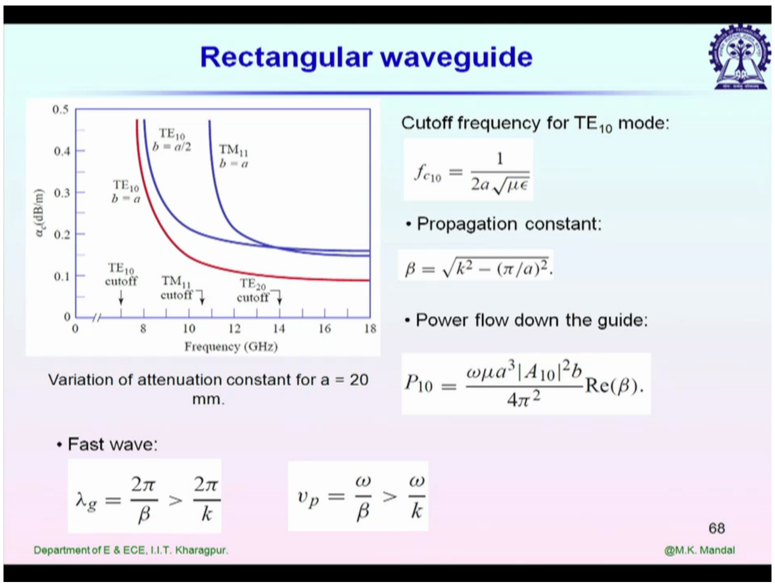

So let us see how they varies with frequency. We are considering different dimensions. Let us consider a X band operation first. So these are the plots of alpha C. We have three different situations, three different dimensions. The for first case B is equal to A that means the broad side dimension is equal to the height of this waveguide. And in second scenario what we are doing, we are changing the thickness to half so B is equal to A by 2. So for the first one we see the plot of alpha C it is having much smaller value compare to what we have for B is equal to A by 2.

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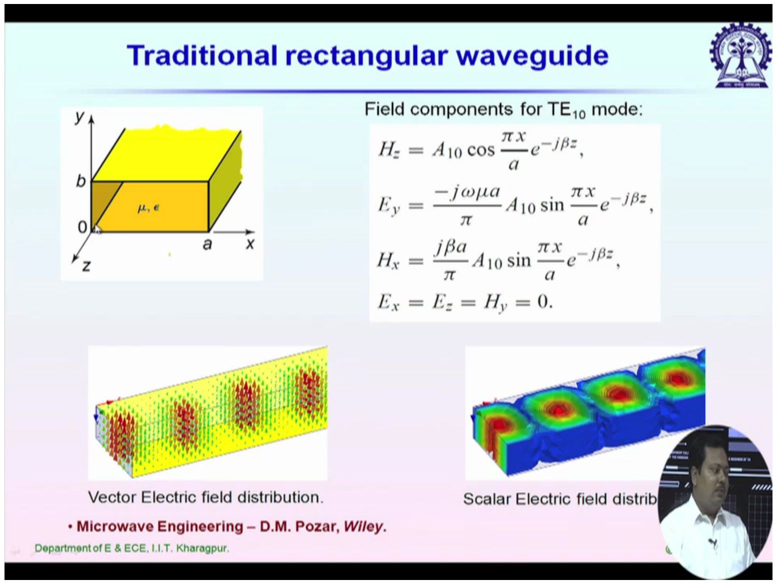

So A is the broad side dimension, B is the thickness of this rectangular waveguide.

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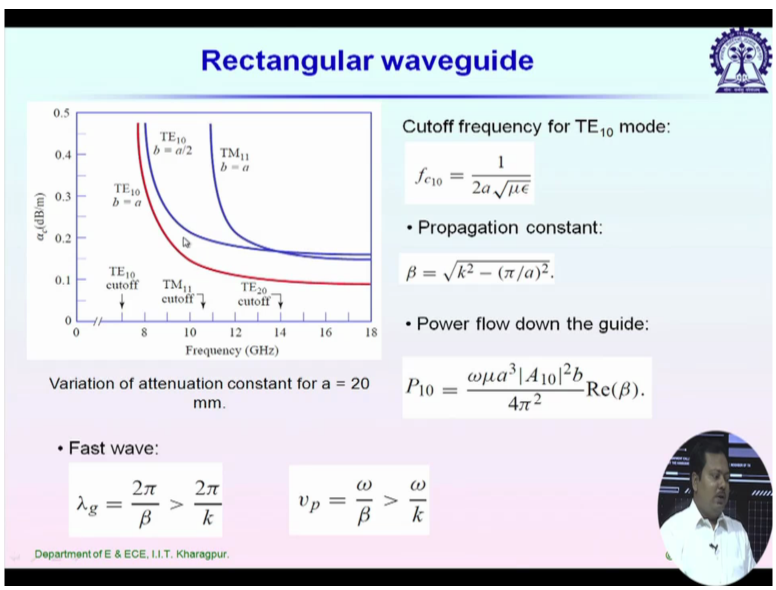

So as we change the thickness B electric field value it increases with decreasing B. And not only that the current density on the metal surface it also increases with decreasing B. So what we expect then the attenuation constant due to this ohmic loss it will be more for a reduced height. As we are see we can see it here also.

So for the same B is equal to A guide the TM 11 mode it appears at much higher frequency. So for both these two cases at cut off frequency it goes to infinity and if we increase frequency, they decreases. Now one of the made main advantages of rectangular waveguide is least loss. So we will not operate rectangular waveguide near its cut-off frequency. Otherwise it will be lossy.

So we have to operate the waveguide at higher frequency compare to FC. But again then we have another limitation than at if we keep on increasing the frequency, at higher frequency we have higher radar modes. The first one let us say.

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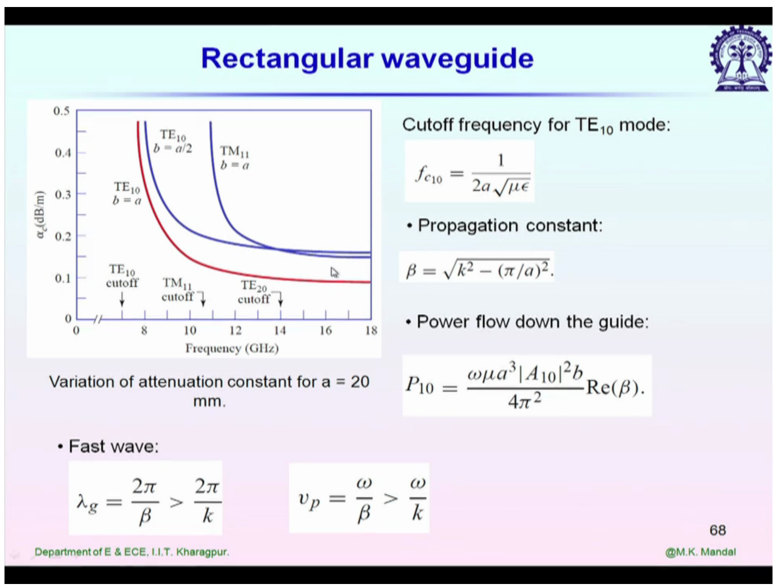

The first one let us say the TM 11 mode it can appear then TE 20 mode can appear so all of these high radar mode excitation they depends on the dimension of the waveguide. And if we calculate lambda g value for each and every case, we have twice pie by beta it is always more than lambda not or in other words, phase velocity it will be always higher than C. so that means rectangular waveguide, it supports only first wave. That TEF TE mode, it is a fast wave mode.

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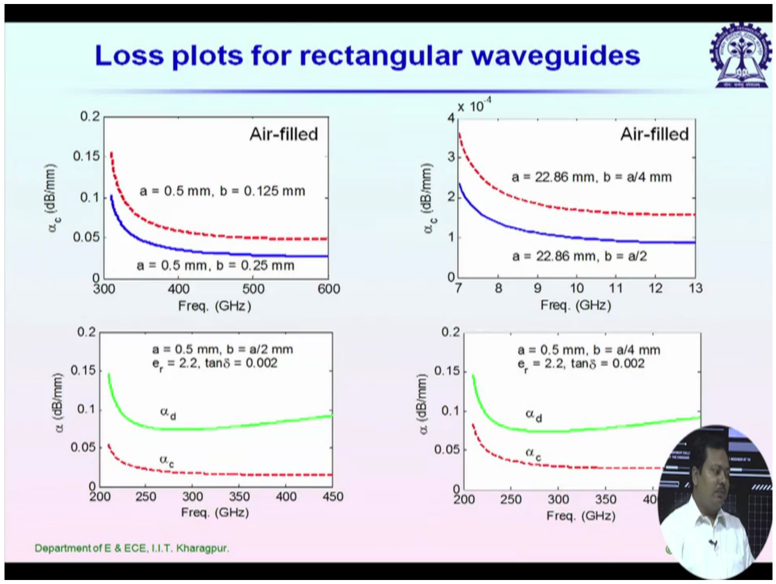

Next, the same plot of same alpha C and also we are plotting alpha D for different scenario. Let us first consider air-filled rectangular waveguide. Two different dimensions one for the X band operation and the second one is in terahertz frequency range. We are considering smooth surface, so no surface roughness is there. Then these are the plots of alpha C for this rectangular waveguide.

The First one for A equal to point 5 millimetre and B is equal to point 25 millimetre and the second one it is reduced height. So B is one fourth of A. As we expected that red line which corresponds to the thinner waveguide it is giving higher alpha C value. Right side for the X band this is for the standard WR90 A is 22.86 millimetre and b is equal to half of this.

We have cut off frequency approximately at 6.35 gigahertz and blue line corresponds to the alpha C variation of WR 90. Now if we reduced the height by the factor of point 5 in that case alpha C increases but look at that values it is of the order of 10 to the power minus 4 db per millimetre and in left hand side it is point 05 to point 1 db per millimetre.

If I operate it in this region about 400 gigahertz so typical loss will be point 03 to point 04 db per millimetre. So if I compare these values with printed lines like micro strip or CPW it will be at least 20 to 50 times higher than rectangular waveguide. It can be a few db per millimetre at this 300 gigahertz or 400 gigahertz frequencies.

So that is why at terahertz frequencies we cannot use printed lines. Now let us introduce some dielectrics inside the wave guiding structure. So the same waveguide with similar dimension but we are using a dielectric material of dielectric constant of 2.2 and the loss tangent is point 002 then the plot of alpha C is this.

And alpha D you see alpha D again its infinite at cut off frequency and then it decrease but it has an optimum point above which it again slowly increases. So this alpha D it represents the dielectric loss and alpha C it represents the conductor loss. So total loss it will be then alpha C plus alpha D.

So look at the cut off frequency values. In the first figure we started at 300 gigahertz and in second figure we have started at 200 gigahertz. Why? Because of this epsilon R. Previously it was air-filled epsilon R is 1 and in second case epsilon R is 2.2 so cut off frequency it decreases by a factor of root epsilon R and right side it showing the same waveguide but with reduced thickness.

Now, B is equal to A by 4 so alpha D and alpha C they have again similar variation. The only thing is that now alpha C is higher compare to the previous case. Now if I combine the effect of both conductor loss and dielectric loss then the resultant variation if I plot again it will be infinite at the cut off frequency.

Then it will have an optimum value approximately at 1.5 times of the cut off frequency then it will slowly increase with frequency. So we can say , we can conclude from this plot that for a given rectangular waveguide dielectric filled rectangular waveguide attenuation will be minimum approximately at 1.5times of the cut off frequency. For example if this waveguide has a cut off frequency of 200 gigahertz then we will expect it will give minimum attenuation at 300 gigahertz.

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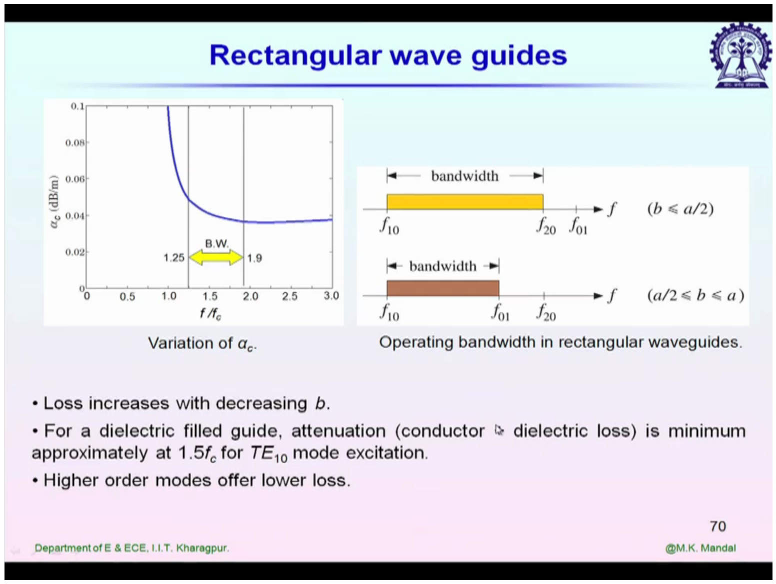

How to choose bandwidth of operation for a given rectangular waveguide? So we are considering here only alpha C that means the air-filled rectangular waveguide we are plotting alpha C versus F by FC. Now let us consider a rectangular waveguide cross-sectional view.

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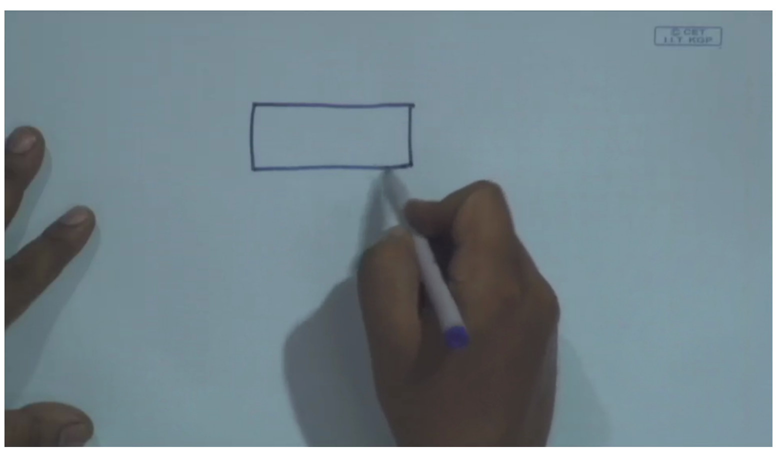

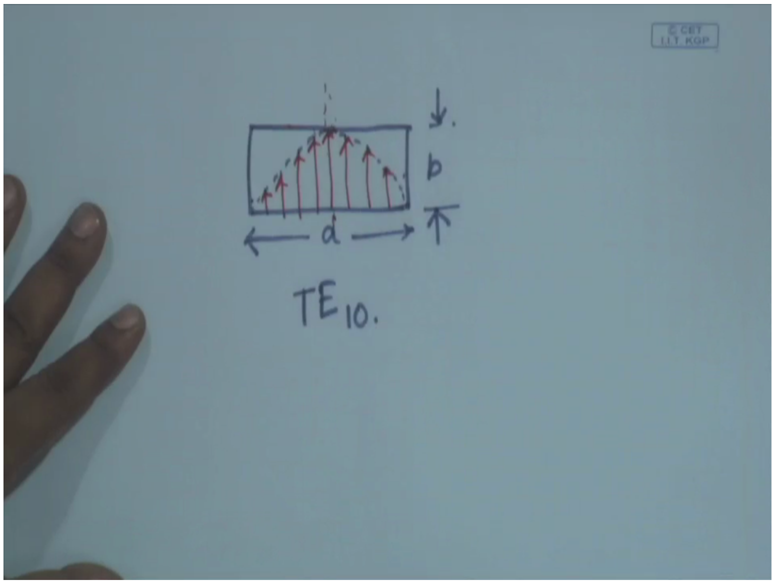

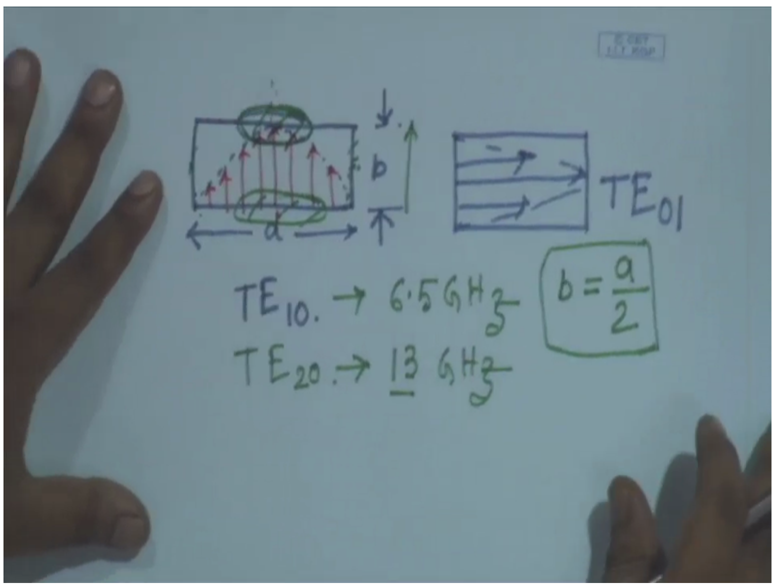

So broad side dimension is A and its height is given as B. If I consider TE 10 mode excitation then if I plot the field strength, it is maximum on the central plane and the direction of electric field it is perpendicular to direction of propagation as well as to broad side. So, on the side walls electric fields are zero.

On the broad side at the mid plane we have highest current density and JC and inside the waveguide we have a displacement current component JD which is maximum on the central plane. So if I calculate the loss or if we want to inspect from which place the conductor loss is coming so it will be mainly from this middle part mainly from this middle part where JC and JD has highest value.

And on side walls the contribution of loss from the side walls it is approximately zero. So if I consider the effect of surface roughness then we have to consider surface roughness should be as small as possible on the central plane. Sorry. Now for TE10 mode the cut off frequency is determined by the broad side dimension A. What will be the next higher radar mode?

It is TE 20mode. If the FC for TE10 mode let us say 6.5 gigahertz for the given dimension we know that the cut off frequency for TE 20 mode it will be just double of this. So 13 gigahertz. So considering the effect of broad side dimension we can use this rectangular waveguide in mono mode operation that means only for TE10 mode excitation from 6.5 to 13 gigahertz.

Now what about the perpendicular dimension if we keep on increasing frequency then we may have also TE like mode in this direction so let us call this mode TE 01 mode. Since its in perpendicular direction. So for TE01 mode, then the cut off frequency will be determined by B and if I want to utilize this whole bandwidth staring from 6.5 to 13 then this B it should be what?

Its maximum value can be A by 2. Otherwise a cut off frequency of TE 01 will be smaller than 13 gigahertz. So that is why for standard rectangular waveguide, we always have B is equal to A by 2. Now if I go back to alpha C plot for air filled waveguide we cannot utilize this whole bandwidth. Why? Because alpha C is infinite at 6.5 gigahertz if it is the cut off frequency. So let us go back to the plot then.

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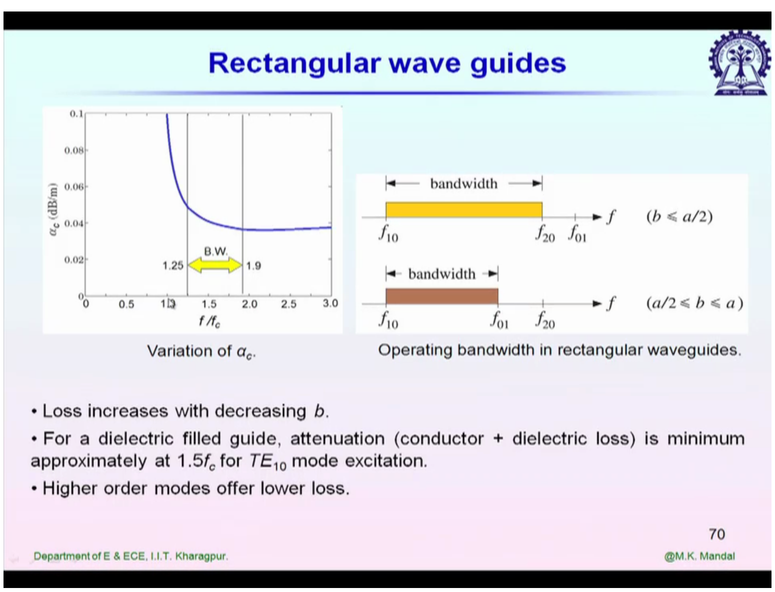

You see if the cut off frequency this is the normalized frequency so F by FC is equal to 1 it represents the cut off condition. At cut off frequency or near cut off frequency attenuation is high so we define the effective bandwidth for mono mode operation where we are expecting only TE10 mode. It starts from 1.25 times of FC to 1. 9 times of FC.

We have a 10 percent margin here to make sure there is no TE20 mode excitation. Either in A direction or in B direction. And if we have now dielectric material inside, for dielectric material again the plot is very similar to this. Only thing is that at 1.5 times of FC it will be minimum, after that it will slowly increase and we define the bandwidth again by this number numerical values one point twice 25 FC to 1.9 FC.

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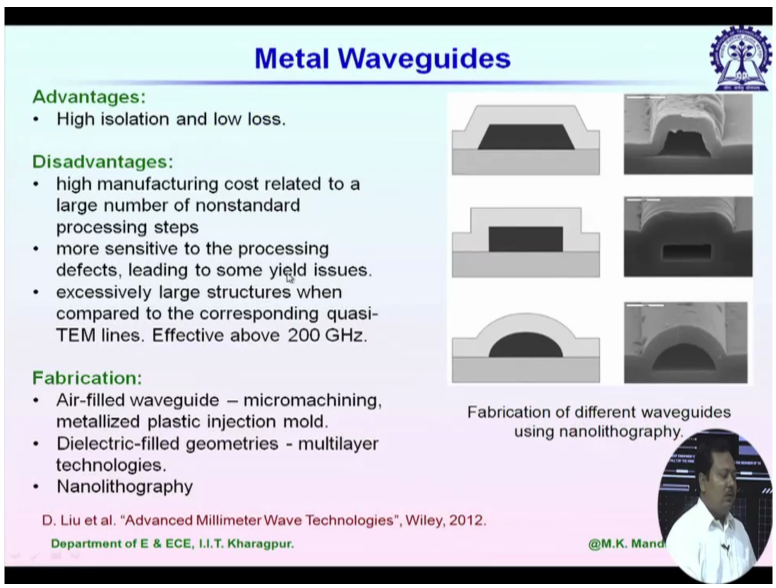

So look at this plot. Ohh sorry.

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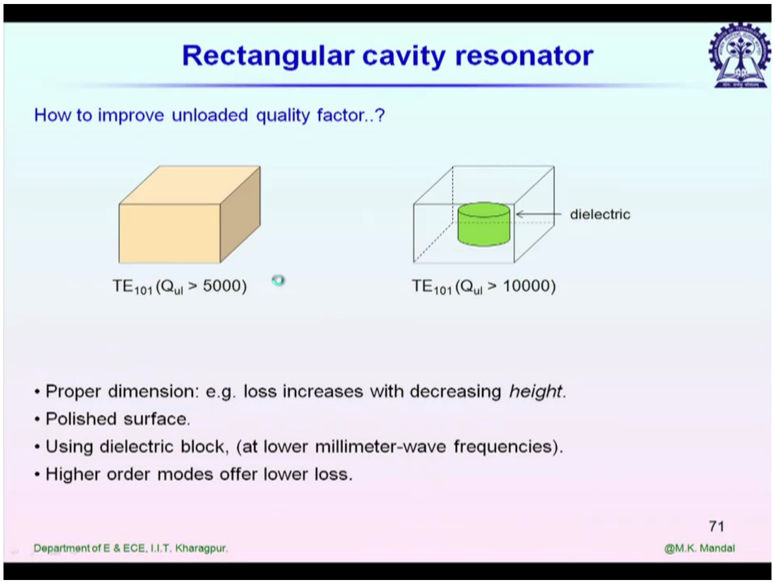

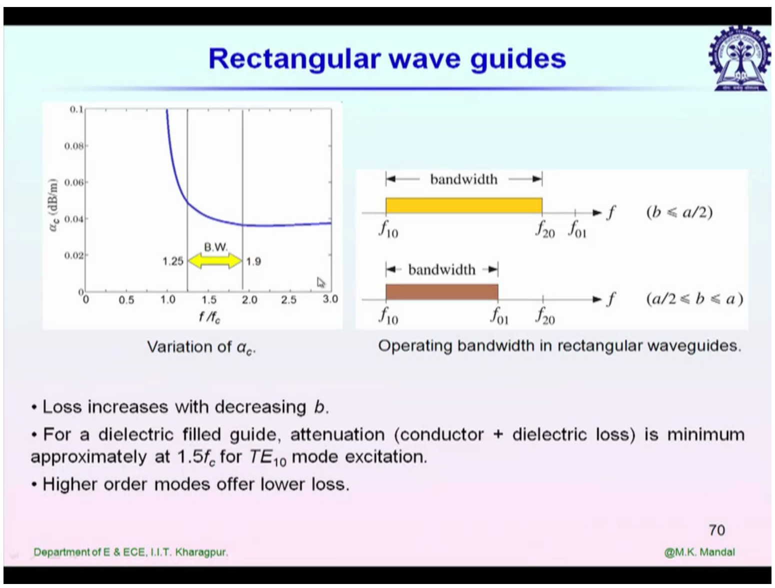

So standard waveguide, its dimension is determined by this cut off frequencies. For example for WR 90 you can calculate then what is the cut off frequency? And accordingly you calculate what is the 1 point Twice 5 25 FC value and 1.9 FC value. You will see that cut off frequency for standard WR 90 its coming approximately 6.35 gigahertz and then the bandwidth its 8 gigahertz to approximately 12 gigahertz.

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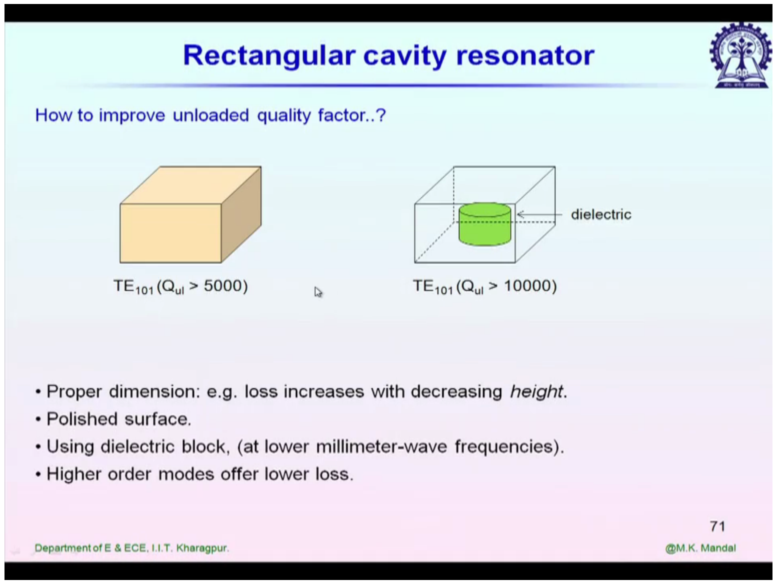

Now let us say we are using these rectangular waveguides to design resonator. We call it cavity resonator. So its a close to resonator. We have metal in all six sides. Since it provides very low loss the unloaded quality factor which is also a measure of loss it has highest value among all the different resonators from different guiding structure.

Typical unloaded quality factor is more than 5000. Now how to improve the unloaded quality factor further? Or how to minimize the loss further for a given cavity resonator what we can do? So then we have to minimize the sources of losses. So for example if I you say reduce hou height, in that case we know that loss will be higher.

So we have to use that standard height at least B is equal to A by 2 Right. We have to use polished surface so that the effect of surface roughness is minimum. So that sound we can minimize the conductor loss. And if we don't use any dielectric inside then we don't have any dielectric loss. Remember if AR its loss tangent value is approximately zero.

So air is almost considered as a free space or lossless dielectric. But if there is water vapour present in air, it becomes lossy because water vapour absorbs electromagnetic wave. So inside whatever material you are using if its air it should be dry or sometime we have people use inert gas and you have to make sure there is no water vapour present inside the cavity, otherwise it will become lossy.

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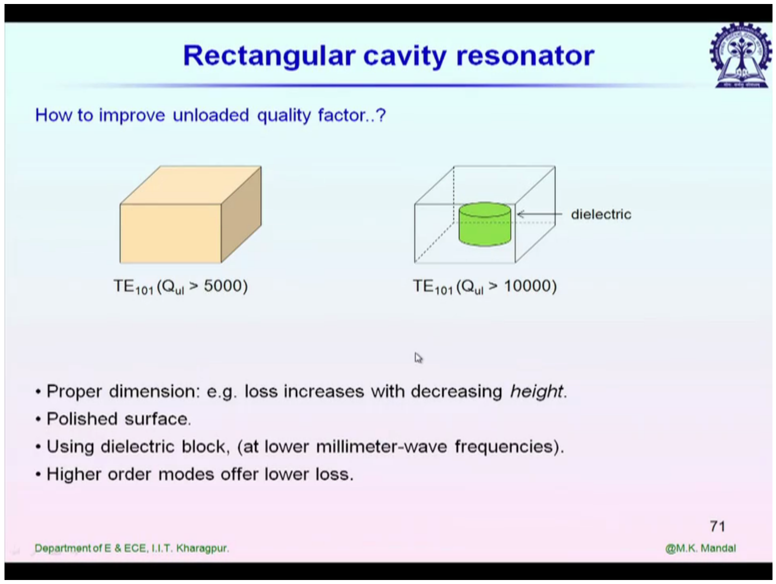

So next there is one more method to increase the unloaded quality factor or minimize loss. What is that method? We have very good some very good dielectric available for which loss tangent is very small. Let us use one such dielectric block inside the rectangular waveguide then what is the advantage?

Most of the electric field inside the cavity it will be confined inside the dielectric and the surface current excitation it will be minimum. So this is our technique how we can decrease conductor loss further. Not only that due to the dielectric dimension of this rectangular cavity it becomes smaller compare to the original one.

The actual value of a resonating cavity, the dimension you can calculate by using any electromagnetic Solver or full wave simulator. It is interesting to know that high radar modes they offer lower loss. So that means if the same cavity if I excite it in TE 20 mode, it will provide lower loss compare to TE 101 mode.

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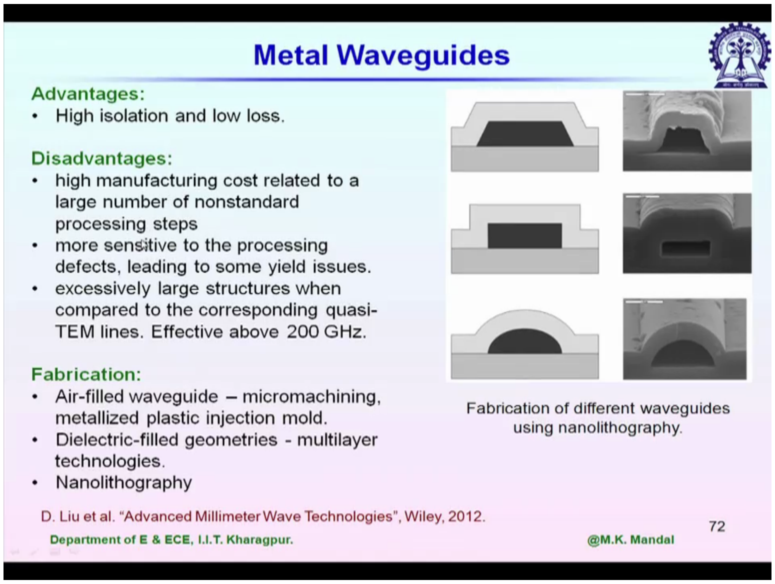

Some typical fabrication example. So now a day's people started using rectangular waveguide for chip to chip communication. So that means as interconnects but rectangular waveguide has a problem that its really very big structure. Its width should be at least lambda g by 2. How we can then decrease the width?

We have to use some higher dielectric constant material inside which has higher epsilon R then we can reduce the dimension by the factor of root epsilon R. Even then we cannot use it as interconnect inside a chip because of its dimension, but above 200 gigahertz and typically at sub millimetre wave frequency range.

And at terahertz frequencies people already started using rectangular waveguide as an interconnect. The main advantage is its lowest loss and why it is above 200 gigahertz? Because of its dimension below 200 gigahertz its so heavy so big that we cannot use it as interconnect inside chip. So here some examples of such waveguide structure.

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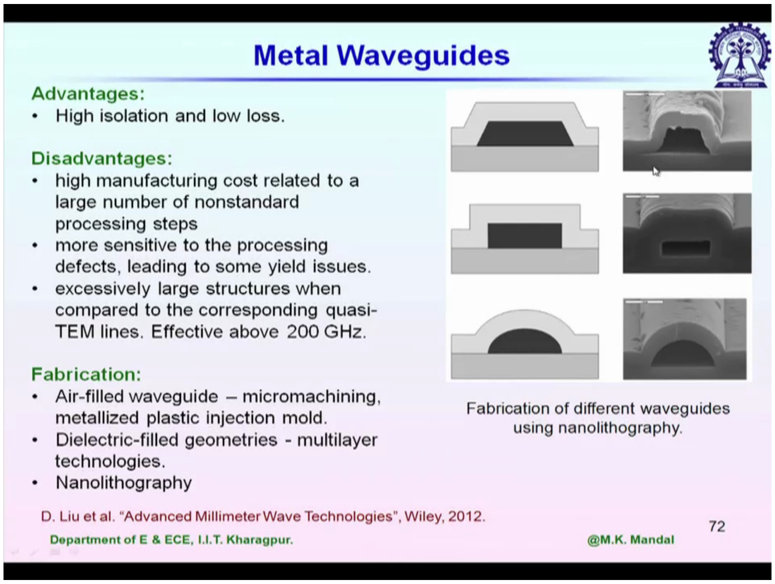

And right side figure you can see. So sometimes also people using air filled waveguide for terahertz application. So these are some electron microscope autograph taken after fabrication or different types of waveguide structure. So the middle one is rectangular waveguide and we also have different shape of wave guiding structure and they are modelled by these structures given by in the left hand side figures. We can determine the characteristics its propagation constant, its cut off frequency, alpha- beta value by using any electromagnetic solver or even theoretically. Sorry.

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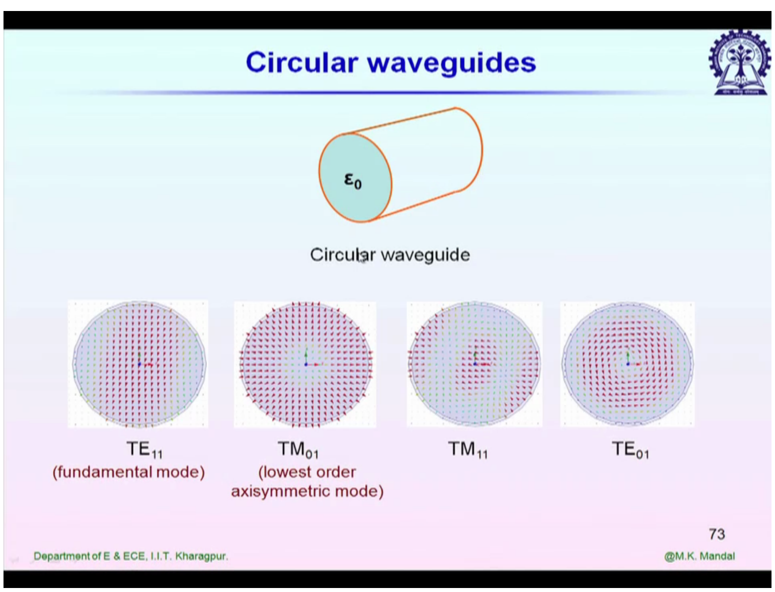

So next one is circular waveguide. We are not discussing in details. For circular waveguide the fundamental mode is TE11 mode. And the next mode is TM 01 mode. If you look at the electric field plots which are shown here over the cross section of circular waveguide so for the fundamental mode it is not symmetric with respect to its axis. The first axis symmetric mode or it is TM01 mode. So for different types of application prople use different types of modes. If we need axis symmetric mode then we have to use TM01 mode. If we want to use just for propagation purpose then people use the fundamental mode that is TE11 mode. Sorry.

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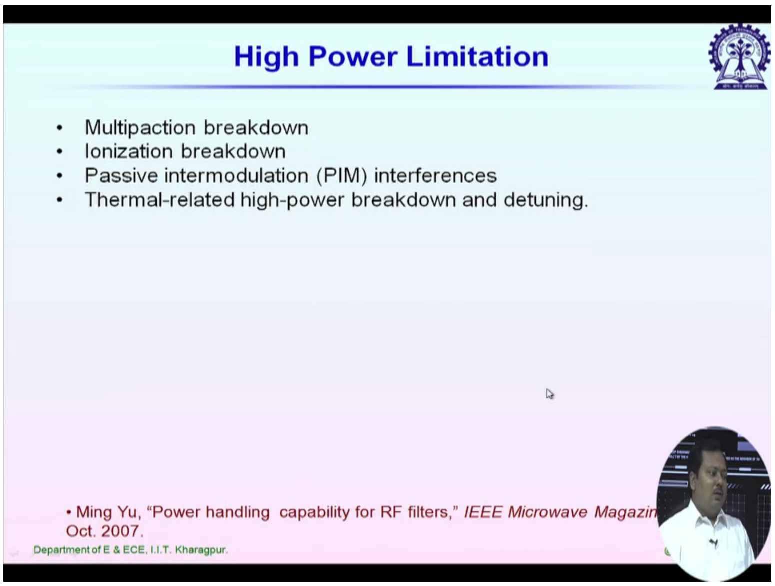

Rectangular waveguide has one more advantage that power handling capabilities highest. So before going to discuss about that power handling capability of that rectangular waveguide let us see what are the factors that determine power handling capability of any given guiding structures. It can be rectangular waveguide, air-filled, dielectric field, it can be any printed line designed on some substrate. It can be dielectric channel, anything. So in general then we have four factors those determine the power handling capabilities of any given guiding structure. So what are they?

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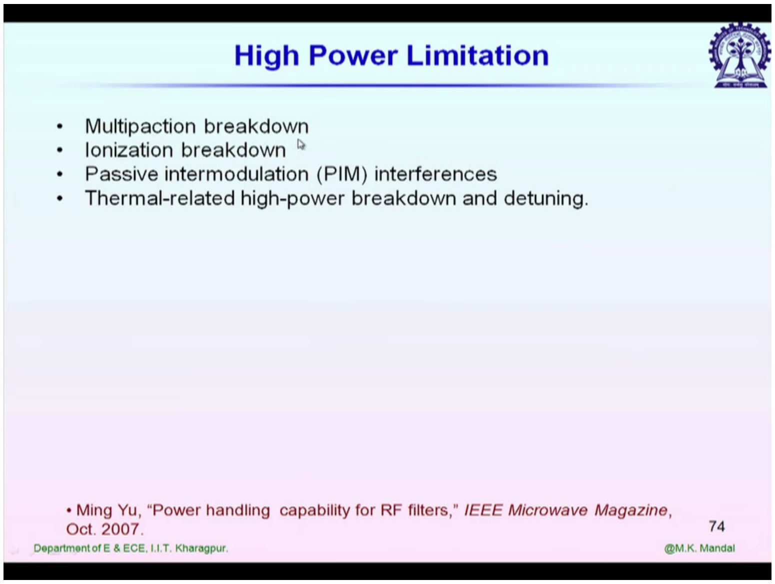

The first one is multipaction breakdown. So this term multipaction might be new to you. I will discuss in details. Then the ionization breakdown or sometimes we simply call it AR breakdown so this is the sparking effect whatever you have seen in day to day applications. Then we have passive intermodulation interference so what is passive intermodulation so by inter modulation we understand mixing of two signals.

So as we observed for mixers, so to translate the frequency we need some sort of non-linearity and that non-linearity we can for non-linearity we can use diode, we can use transistor but for a passive device like rectangular waveguide or for a printed circuit board, guiding structure. What is the source of this inter modulation? The source is different types of metals.

So if there is any impurity it may be very small, its work function is completely different than hosting guiding structure like copper. So they form some non linearities. So it can be a metal metal junction or metal dielectric junction and it provide some nonlinearity. But the effect is very small. But sometimes the small effect also we cannot neglect.

For example you consider a mobile base station application or a satellite transponder application where transmitting power is of the order of watt or of the order of kilo watt. And the received power it is nanowatt or sometimes for satellite application it can be as small as pico watt just below noise noise (())(25:23).

So in that case for your receiver circuit, receiver is tuned to IF frequency and for IF frequency it is much small. Right? So for the mixer it will generate your IF which is the difference between the local oscillator frequency and the incoming RF signal. Now somehow let us say from your transmitting signal we have the inter modulation product and a frequency component is being generated due to this inter modulation which falls in your IF band.

So since its component is very small, this is due to the passive intermodulation for normal application we will simply neglect it. But for this type of application when transmitter and receiver they seats together even a slight leakage that will be enough to destroy your receiver because it is falling in the IF band.

And the power leakage from your transmitting side it is small compare to the transmitted power but not that small compare to the received power. It can be more than that. So it can completely damage your receiving circuit. So next one is thermal related high power breakdown and detuning.

If we change temperature then we have seen that dielectric constant, its function of frequency and its epsilon R will change with frequency. So the operating frequency of the component it will also change. Now usually what happens? If we again bring back the original temperature the dielectric constant it also comes back to original value.

But there is a limiting temperature above which the dielectric it completely changes its properties. We call it the glass breakdown temperature or transition temperature. And also we may face breakdown effect that is the dielectric breakdown so it simply bond the dielectric. Now let us take a short break then we will discuss about this different effects in details.