Millimeter Wave Technology.
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Lecture-11.
Guiding Structures (Contd.)

Okay so we are continuing with microstrip line and then after that we will see another popular printed line with which is CPW lines. So with the microstrip line or CPW lines or any other type of printed lines so the problem we face at the millimetre wave frequencies is higher loss. So already we have seen that dielectric loss.

Conductor loss both increases at millimetre wave frequencies and not only that we have one more problem due to surface wave. So if the thickness of the given substrate is thicker compare to the wavelength then the excitation of surface wave is more. So as the frequency increases then we should choose a much thinner substrate to avoid surface wave generation.

So before going to other issues for microstrip line those determines the high frequency limitations of a microstrip line. So let us discuss what are the properties will be having for a microstrip line resonator? So resonator we used in different applications so for example by using resonator we can also design antennas.

We know rectangular cache antenna, dipole antenna so all examples of different type of resonators. So in this antenna applications intentionally we won't hire radiation loss but the same resonator we can also use to design filters. Typically band pass filter. In those application then we don't want any radiation. So if there is any radiation that will be undesired.

Then how to keep radiation minimum from this type of applications? Another important application is the tank circuit which we use to determine the frequency of an oscillator. So let's first see what are the effects we will be facing at millimetre wave frequencies for a microstrip line resonator. So we are going to consider one microstrip line of length lambda g by 2.

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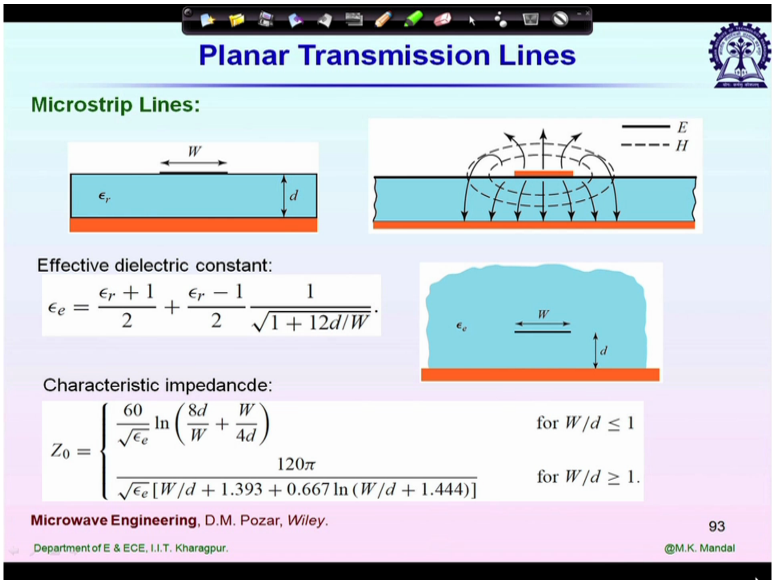

So let me draw the top view.

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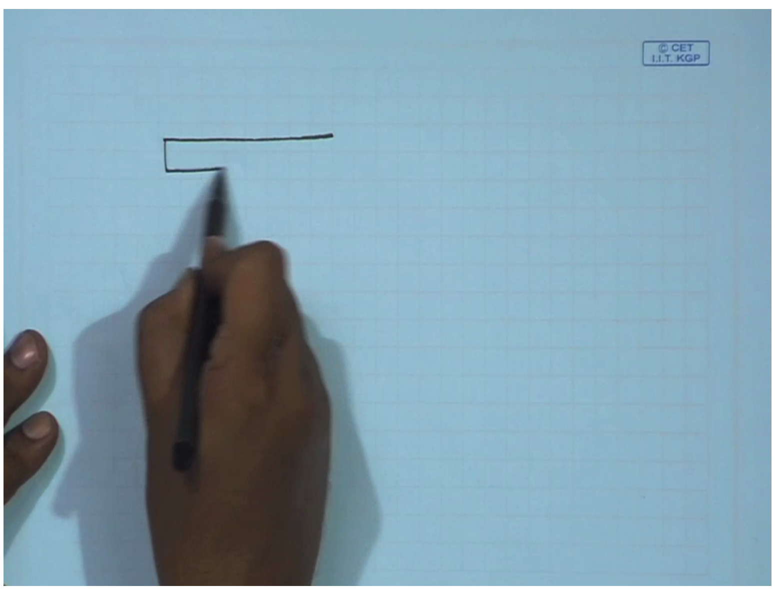

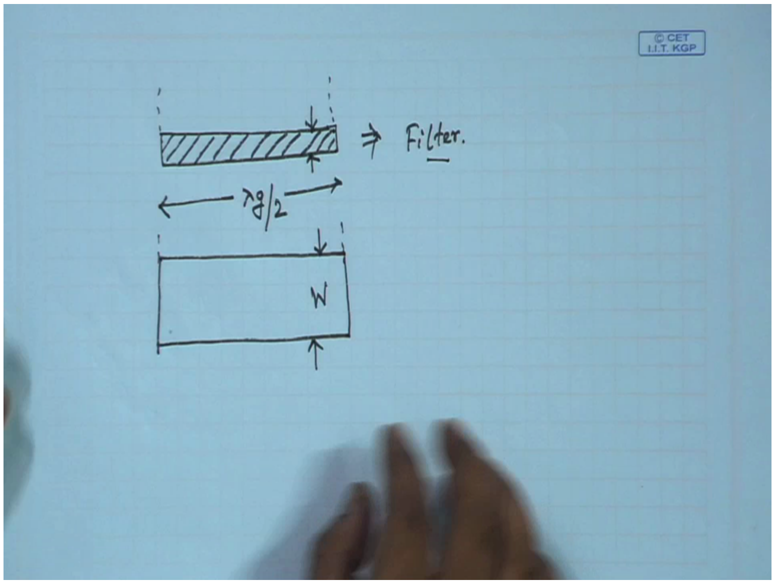

So its showing a microstrip line. Its top view so I am just drawing the metallic strip part. When its length is lambda g by 2 it will resonate now looking at the microstrip line both ends are open circuited, so will be having high electric field at this plane and right hand side plane. So from the fencing field if the electric field and magnetic field they are in same phase, there will be some radiation.

And practically what we see, if we keep on increasing the width of this microstrip line resonator then the part of magnetic field and electric field on these two planes which is in air and in same phase increases. So radiation will increase. So what we see then, if I increase the width of this resonator W then radiation from both of these ends will increase.

So if I want to design one antenna we will choose a higher W but, if I want this resonator for filter applications in that case the width should be small. But if its too small we face one more problem. What is that problem? So in that case conductor loss will increase.

So in practice what we do for filter applications or for oscillator applications we use a full wave simulator or electromagnetic solver and then tune the W for minimum loss and for minimum radiation. So this W value its an optimum value between the thinnest line and this thicker line. So now let us see at millimetre wave frequency we have some other problems.

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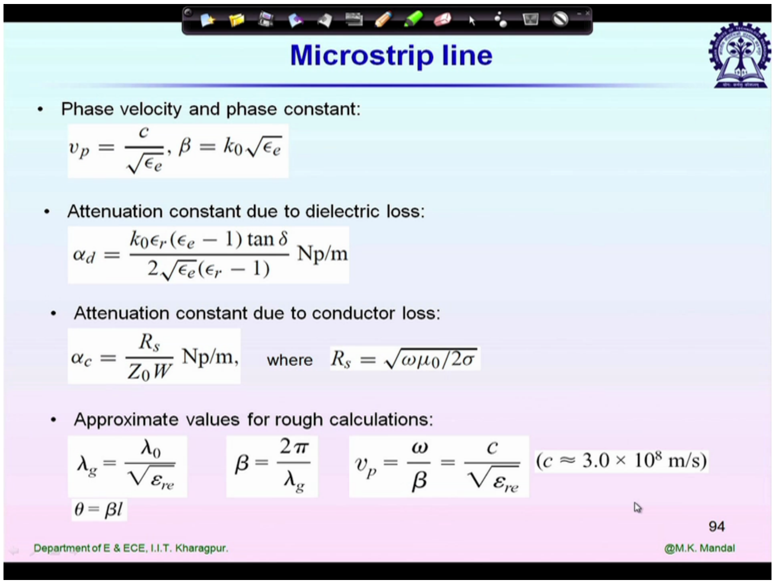

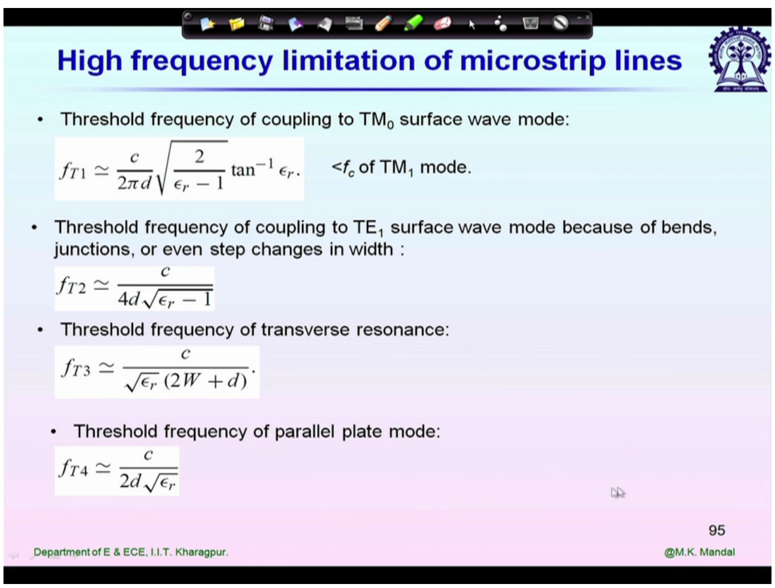

What are those problems? So we have mainly four reasons those determines the high frequency operation of a microstrip line. The first one is due to the threshold frequency of coupling to TM0 surface wave mode. Now for a surface wave mode transfers magnetic excite mode excitation. What we have seen that?

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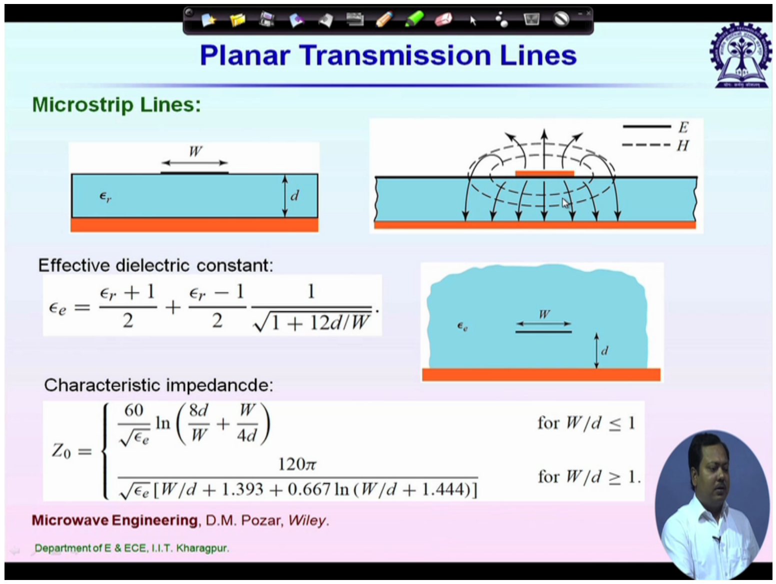

Let us say this is the microstrip line and the wave propagation direction in Z direction then for TM mode we have two different components of electric field. One component is in direction of propagation. So EZ component and another component is perpendicular to the ground plane which is maximum on the ground plane.

Now if I look at microstrip field lines we also have this perpendicular field components so the surface wave TM0 mode it will be easily excited by microstrip line. Now TM0 mode it does not have any cut off frequency. So we cannot avoid this TM0 mode excitation. The excitation of TM0 mode of course it depends on substrate thickness if the thickness increases, in that case will be having more TM0 mode excitation. So we can't avoid TM0 mode excitation.

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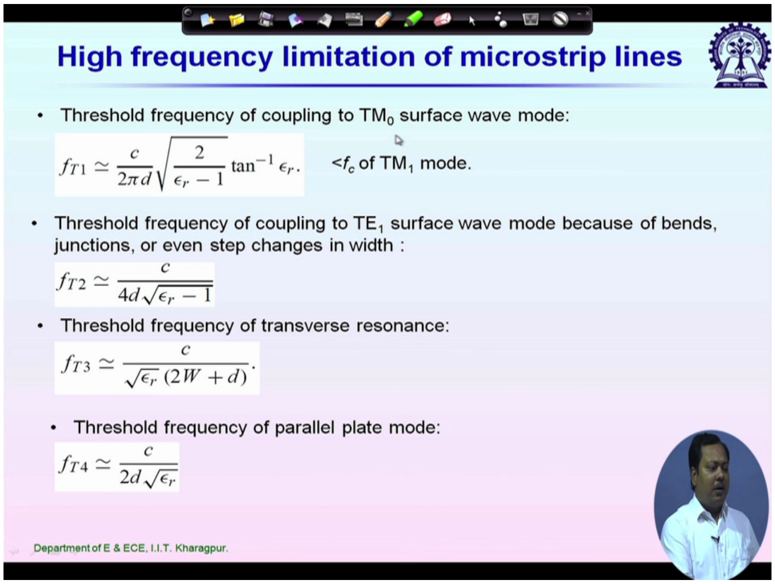

But at least we can avoid other higher radar mode excitation like the first one is TM1 mode which has a cut off frequency. so the first limitation it comes from the cut off frequency of TM1 modes which is given by this equation FT1 approximately this is equal to C by twice pi D where C this is the velocity of light in free space and D this is the thickness of the substrate and epsilon R this is the dielectric constant of the substrate.

So once we know the substrate parameter so then we can calculate what could be FT 1 for that given substrate. Next one this is due to the threshold frequency of coupling to TA TE1 surface wave mode so now if I again go back to microstrip line field configuration.

If you remember for TE mode TE type surface wave mode we have only one dominant electric field component which is parallel to the interface so if I look at the microstrip line field configuration so electric field component of surface wave is parallel so that means its perpendicular to dominant component of microstrip line.

So what we expect then almost no excitation of TE type surface wave mode from microstrip line. Because this two field components are orthogonal to each other. And that's why usually for a straight microstrip line they are won't be any excitation of TE mode but now consider bend.

So several times we will be using the different types of junctions like T junction, Y junctions, X junctions and microstrip line bends whenever we are going to design any components in printed lines. Now this bend is associated with different type of field components.

The orientation of this flanging fields it will change and they can easily excite TE modes. Now again for TE0 mode we don't have any cut off frequency so we can't avoid TE0 mode excitation. So only thing is that we can keep it minimum by choosing a thinner substrate so at least what we can do?

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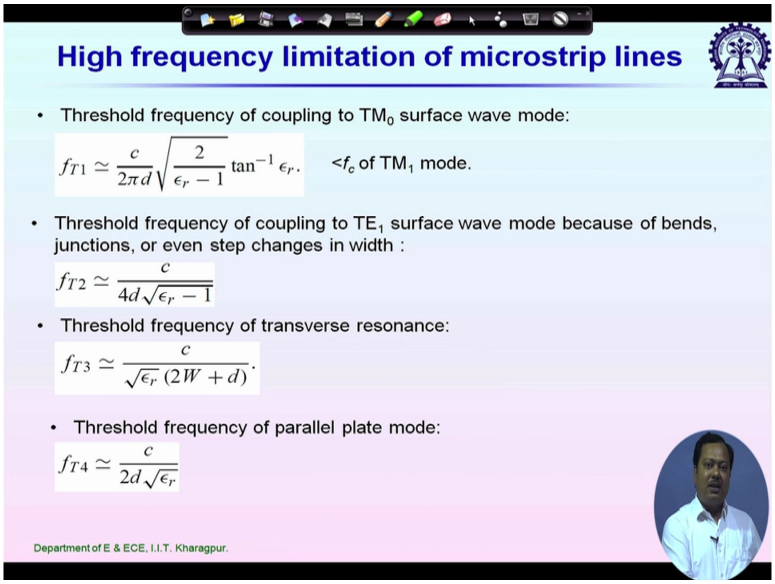

We can avoid excitation of TE1 mode. So in this equation FT2 this it comes from the cut off frequency of TE1 mode and which is given as FT2 nearly equal to C by 4 D square root of epsilon R minus 1. So for a given substrate again we can calculate what is the FT2? For a microstrip line we are expecting in that substrate. Next threshold frequency of transverse resonance so let me first explain what transverse resonance is. Then I will come to threshold frequency. So before microstrip line

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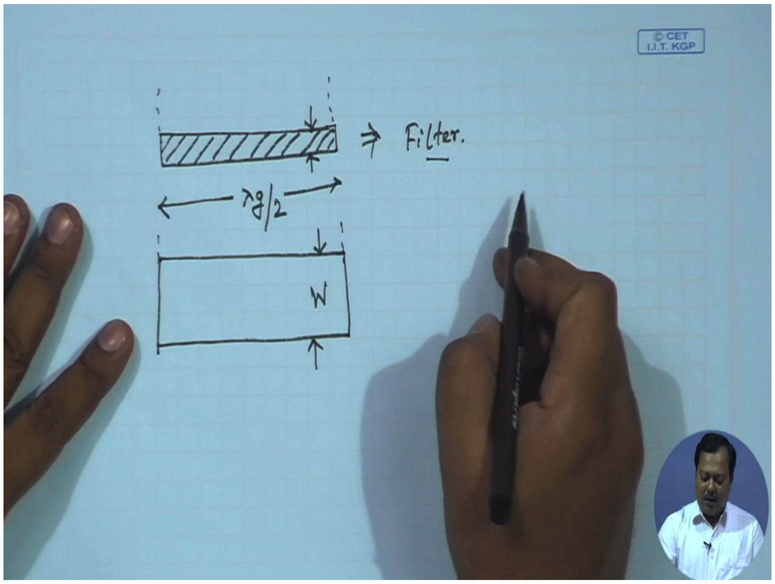

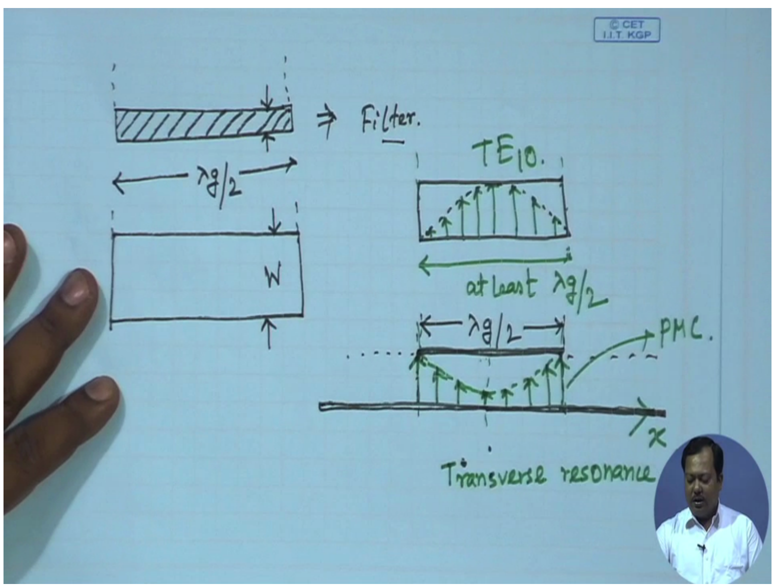

Let us recall what is the field configuration for TE10 mode inside a rectangular waveguide? So if I draw the field strength it varies sinusoidally and it is maximum on the central plane and then left and right hand side it decreases. So these electric field components it becomes parallel to the sidewalls of a rectangular waveguide.

So obviously then electric field component will be zero on the side walls and this length broad side length of the rectangular waveguide. It should be at least lambda g by 2. Otherwise it will not support this TE10 mode excitation. Now consider a microstrip line. So microstrip line let's say its too wide compare to the wavelength. How wide?

Its length sorry its width is now given as approximately by lambda by 2. So this is the strip. Its sitting over a dielectric and this is the ground plane of the microstrip line. I am drawing the cross sectional view. Now if I compare these two figures for rectangular waveguide. We have metallic side walls so that means we ca can model it by electric walls TEC.

And for microstrip lines it looks like open circuit so we can model this two surface by PMC. So in this case this microstrip line it can supports transverse electromagnetic wave but the field configuration or the variation of electric field along X it will be different because we have open circuit at two sides. So how is the field configuration now?

So if I if I draw the field strength so it will be maximum at the two side walls where we have PMC. And it will be minimum on the central plane. So this is called the transverse electromagnetic resonance or simply we call it transverse resonance. So for this the condition is that the width of the strip of a microstrip lines it should be at least lambda g by 2. So it's highly possible when we are dealing with millimetre wave frequencies. Now let's go back to slide.

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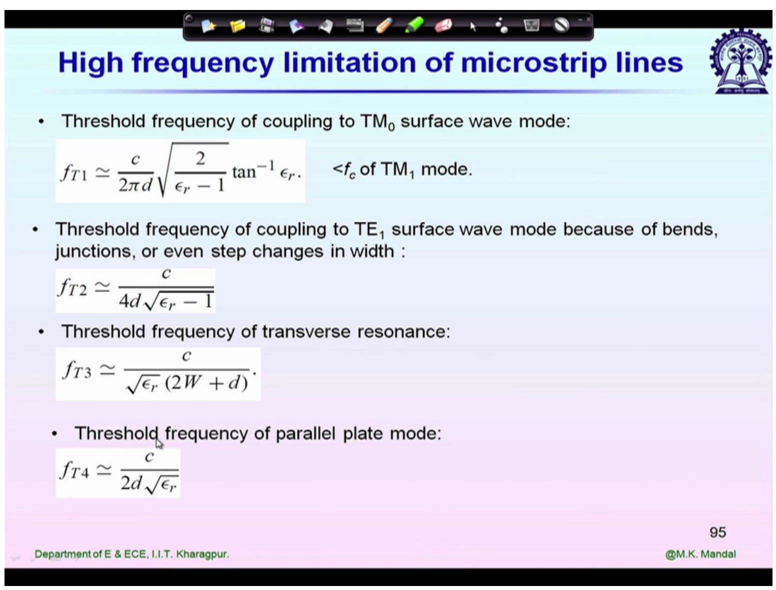

So the threshold frequency of transverse resonance it's given by FT3. It is approximately C by root epsilon R into twice W plus D. Where W this is the width of the microstrip line. So you see then it depends on the width of the microstrip line. We have a new parameter which was absent in FT1 or FT2.

So if I consider a 50 ohm line then we have to calculate what is the corresponding width in the given substrate? And D is the thickness of the substrate. So if I increase the thickness of the substrate obviously for 50 ohm line we have to increase w. If we choose lower epsilon R in that case also we have to increase W so that means even if I thicken D for smaller epsilon R FT3 will decrease.

And not only that in when will be designing millimetre wave components in that case we don't only deal with 50 ohm line. Sometimes we have to use a smaller impedance as small as let's say 35.35 ohm. Or when we are designing filter sometimes also we deal with much lower impedance. Let's say 20 ohm so now small impedance it is associated with large width.

So for a practical microwave circuit then what we do? We have to consider the widest section of the microstrip line and then calculate what is the corresponding FT3? So accordingly you have to choose the substrate for the given frequency of operation.

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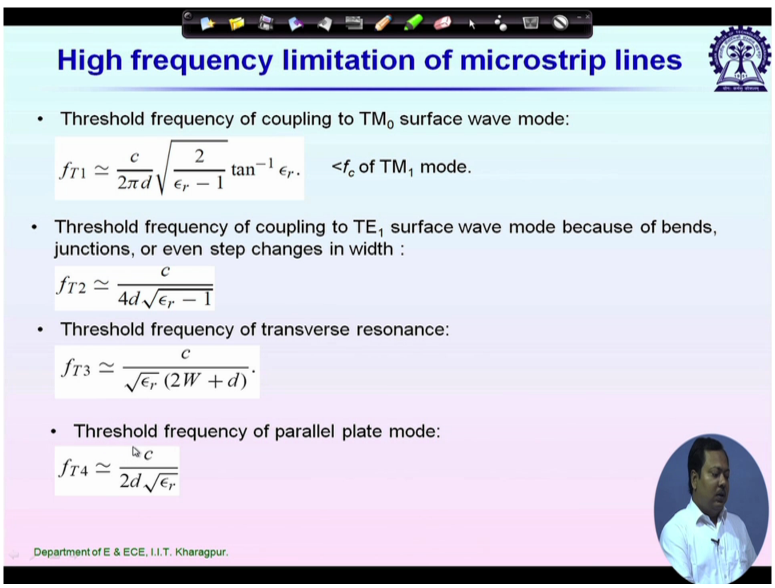

And next the fourth one threshold frequency of parallel plate mode so do you remember that parallel plate excitation? So if we have metal on top and bottom of the substrate it can also support TEM wave propagation. It can also support TE and TM wave propagation. So microstrip line its being a strip parallel to ground plane it can also support similar mode but TEM mode its already supporting.

So next then we have to consider the cut off frequencies of TM mode and TE mode. So we are not expecting that microstrip line will be supporting that parallel plate mode excitation due to TE wave and TM waves. So we have one more threshold frequency due to that which is given as FT4 nearly equal to C by twice D square root of epsilon R.

Where D is the again thickness of the substrate so it depends mainly on the thickness of the substrate and the dielectric constant of the substrate now for a given substrate if we calculate all these four frequency components in most of the cases we will see FT3 is minimum. So the minimum among this four determines the maximum operating frequency for that given substrate. Not only that we consider some margin at least into 20percent. So these keep it in mind.

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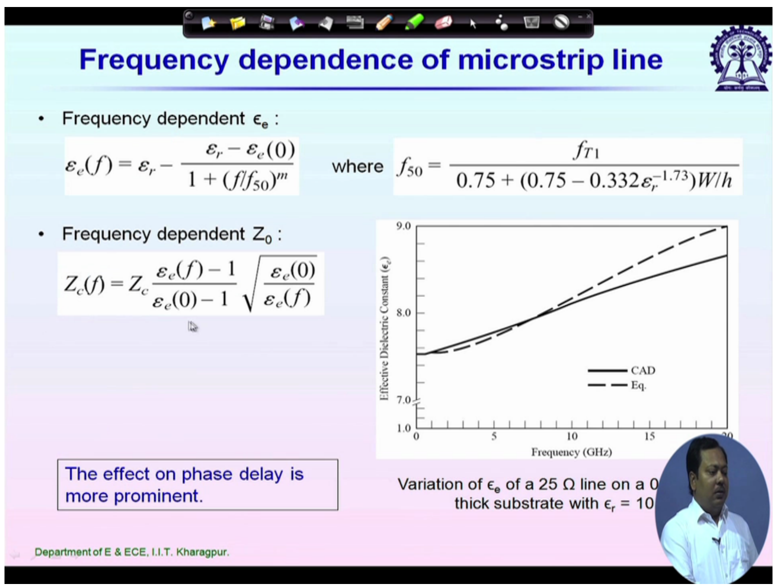

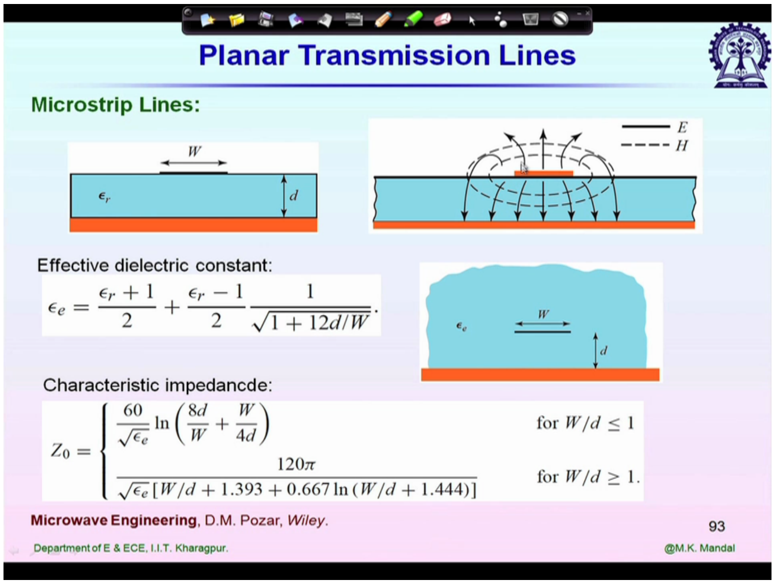

So next the variation of epsilon E and Z for a given substrate what we have seen from the electric field plot in this slide most of the electromagnetic wave it is confined inside the dielectric but some of them also in air. That's why we define an effective epsilon and for a effective epsilon for this microstrip line. And whose value is smaller than the epsilon R of the substrate and higher than air. Now if the flanging field is less in air in that case epsilon E will be more close to epsilon R value. Right? So if we have less flanging field that time we can say epsilon E is very close to epsilon R.

Now for a given substrate if I change the operating frequency then the flanging field component it changes, if I increase frequency then the thickness of the substrate with respect to lambda g it is increasing then we will be having less flanging field in air with increasing frequency. So what do we expect then epsilon E it will be more close to epsilon R or in other words epsilon E it increases with frequency. So we have a plot here. Let's see

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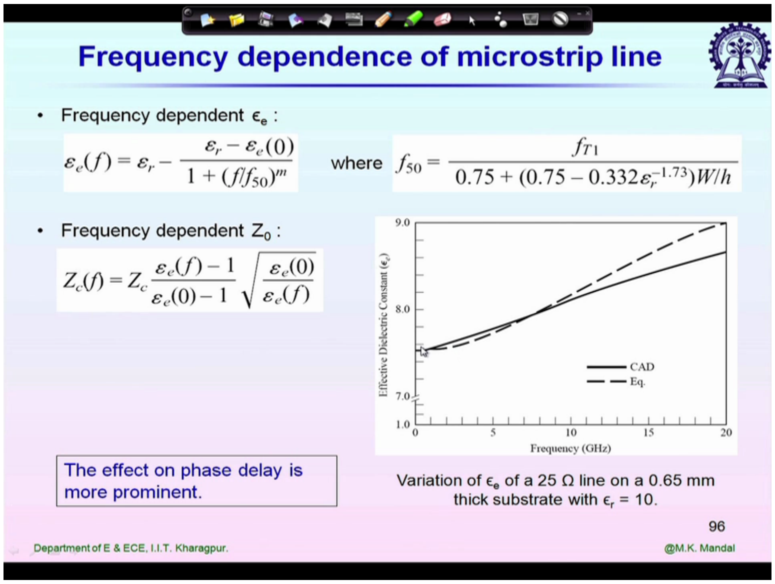

So this is the calculated epsilon E from this closed form expression so look at the closed form expression. Epsilon E it's a function of frequency. And it's given by epsilon R minus this correction factor. Epsilon E 0 it means the effective epsilon at DC when frequency tends to 0. And F by F 50 where F 50 is given here FT1 is the cut off frequency defined as this first equation.

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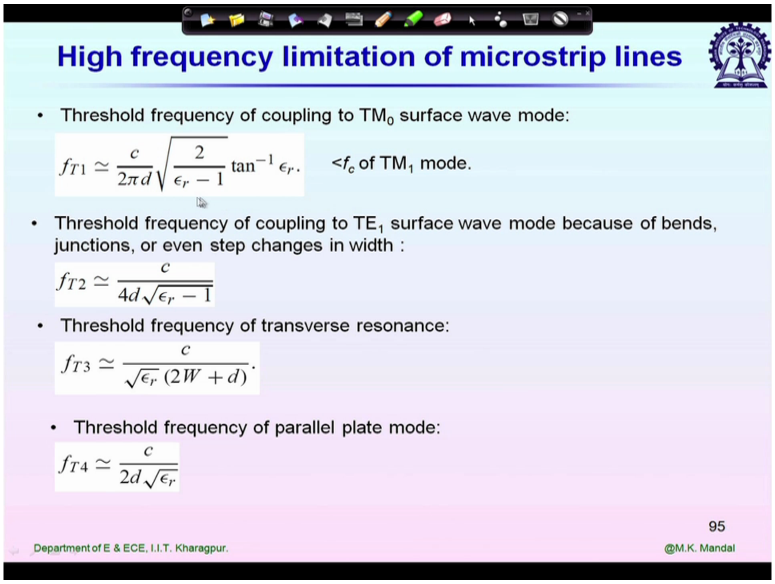

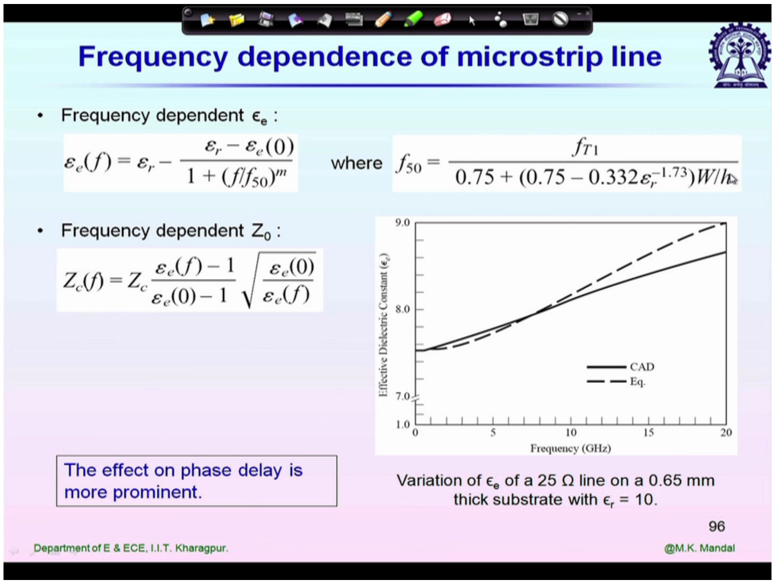

And W is the width of the strip here H is shown instead of D represents the thickness if the substrate. Now if we plot epsilon E it increases with frequency. Its shown by this dashed line. We can correctly determine epsilon E by using any full wave simulator and we also plot it here that epsilon E by using full wave simulator so it almost follows this equation.

And we see what that it increases from DC to at 20 gigahertz start at 0 it is approximately 7. 5 and it increases almost to 8.5 at 20 gigahertz. So epsilon E its a function of frequency and it increases with frequency. The problem what we face characteristics impedance it almost remains constant but the problem we face with beta. Beta it becomes a function of frequency.

If we dint consider the accurate value of epsilon E in that case whatever beta or lambda g we are calculating. So that will be with error. And whatever length we are considering we have to correct it again noting down the actual or accurate values of epsilon e. Next see the variation of Z nought.

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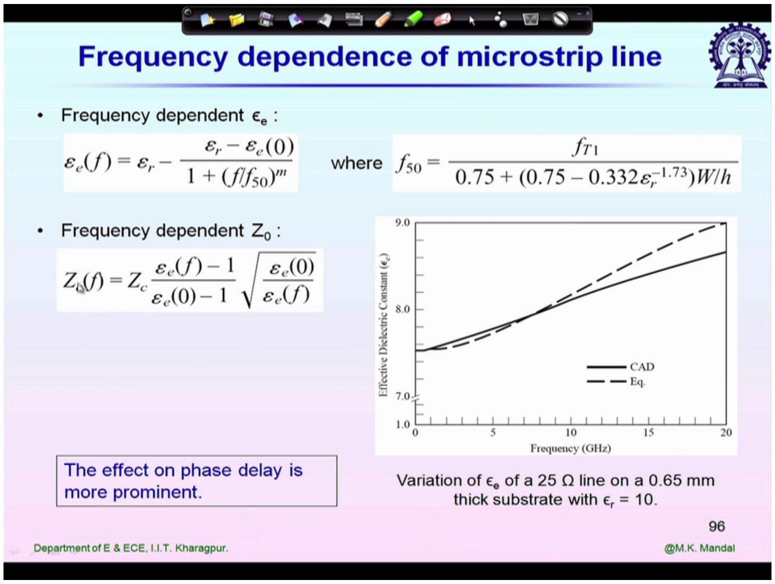

So the Z nought so the Z nought it is also a function of frequency. But the variation of Z nought with frequency is not that significant like epsilon E so in most of the cases we simply neglect the variation of Z nought.

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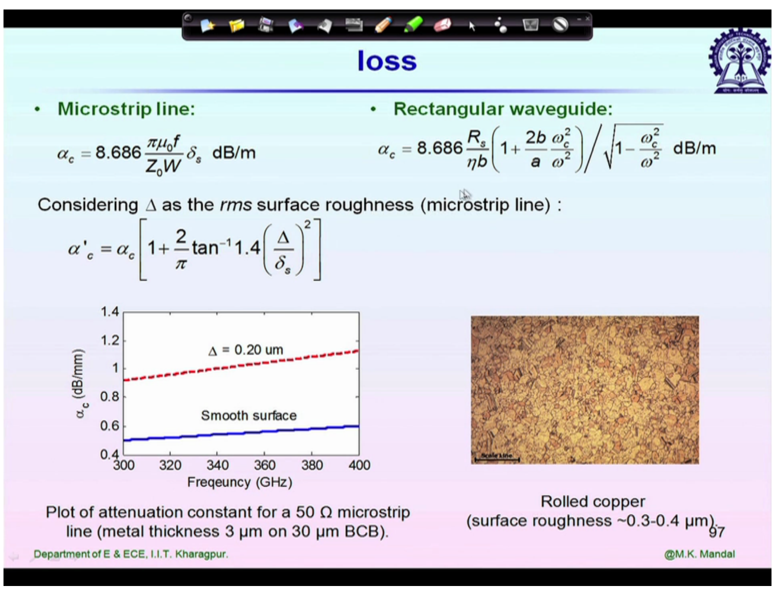

Now what are the sources of losses for microstrip line. Already we know the reasons. So the first one is conductor loss and why? Because with increasing frequency skin depth decreases.

And the surface resistance will increase so conductor loss will increase and if we choose a thinner substrate what will happen? To suppress the surface wave mode thinner substrate it it associated with higher electric field value. Why? Let us consider again one simple diagram.

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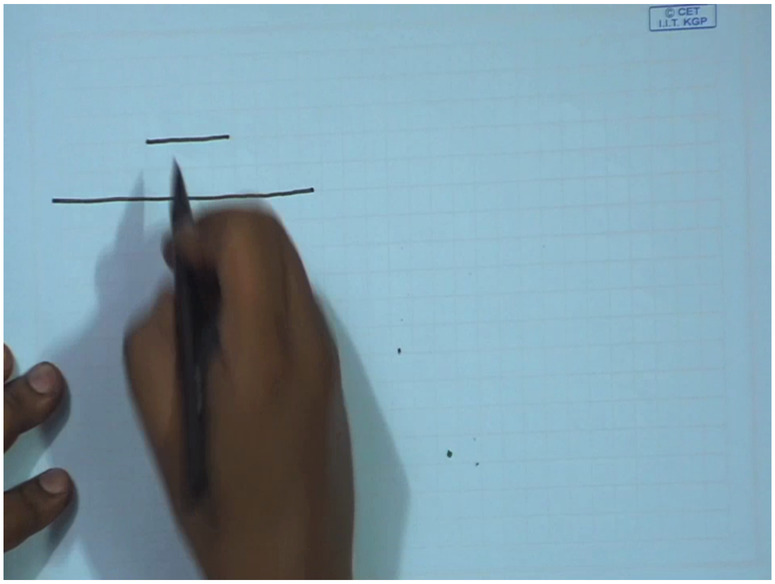

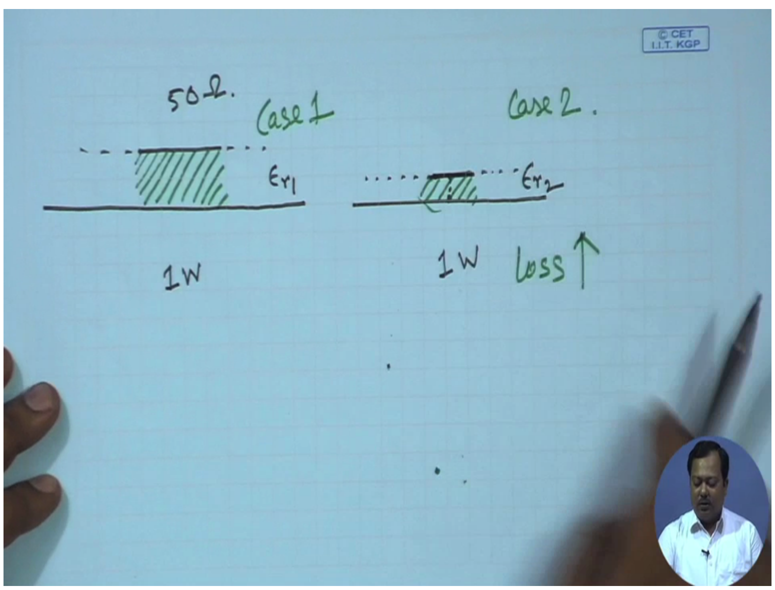

So we have two scenarios. In first case this is substrate one. We are considering again 50 ohm transmission line and in the second case for substrate two but we are considering a thinner substrate here. Epsilon R for the first one and second on we are keeping it same.

Now if I send 1 Watt of power through the microstrip line one and microstrip line 2 and in this case electromagnetic energy is mainly confined below this strip and here also same thing. Now since the cross sectional area in the second case is much smaller. What we expect that displacement current of the electric field inside the dielectric it will be much higher compare to case one.

The induced current JS inside the conductor that will be also higher compare to case one so in this case then loss will increase, conductor loss will increase. Not only that since we are considering higher electric field inside the dielectric in this case dielectric loss also will increase. So in general the thumb rule is that if I use smaller cross sectional area loss will increase. So let's go back to slide.

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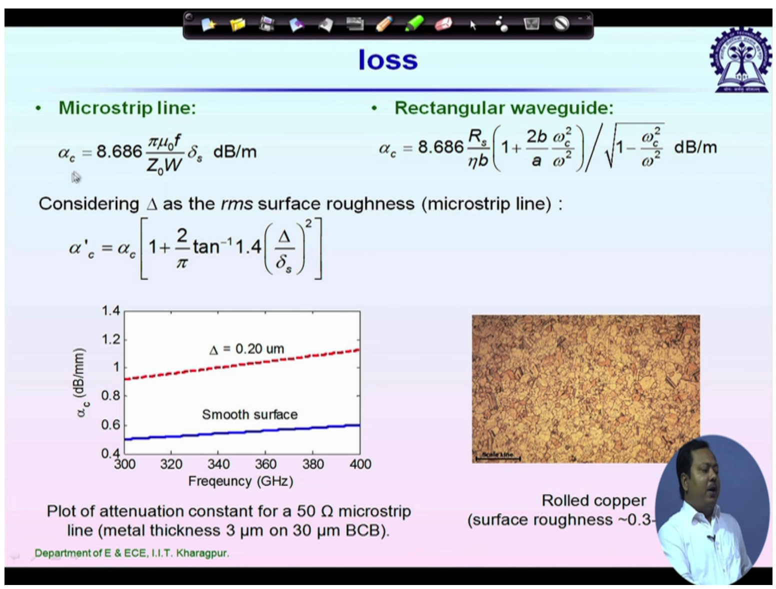

So for microstrip line alpha C it represent the attenuation constant due to conductor loss this is 8.686 multiplied by this quantity. So its function of frequency you see here we have two frequency dependant parameter one F and another delta S the skin depth. But skin depth it varies inversely with square root of frequency so as a result overall alpha C it inceases with square root of F.

And not only that it's a function of characteristics impedance as well as it's a function of width of the microstrip line. As we expected that if we use thinner line we will be facing higher conductor loss. Now remember this closed form expression is derived considering a smooth surface, but practically whatever surface we use that is not smooth.

We always having some rough surface. This is one example of rolled copper. So if you look at the surface we can't consider it as a smooth surface typically at millimetre wave frequencies where skin depth is already very small. If you remember for copper at 100 gigahertz the skin depth is just point 21 micrometer and for this rolled copper typical surface roughness it varies between point 3 to point 4 micrometer.

So umm the effect of surface roughness is that increased alpha C. Let us consider one example, here we are plotting alpha C in DB per millimetre versus frequency. We are considering the terahertz band just above 300 gigahertz so where the skin depth is much smaller compare to that this surface roughness.

So let's say the surface roughness capital delta it is defined as point 20 micrometer then if I consider smooth surface according to this formulae so then the raw loss is roughly point 5 to point 6 DB per millimetre over 300 to 400 gigahertz and it increases to point 9 to 1.1 DB per millimetre.

If I consider surface roughness of point 20 micrometer and for this example we are considering a BCB substrate and 50 ohm microstrip line the metal thickness is 3 micrometer and the dielectric thickness is 30 micrometer. So what should be the optimal thickness of metal whenever we are designing any printed lines? We know the concept of skin depth so at 100 gigahertz for copper we can say that surface wave that surface density of current it is already 1 by E times at point 21 micrometer depth.

Now if I use let's say unnecessarily thicker substrate let's say if you 100 micrometer we know that there won't be any current inside so in practice we use a thumb rule that the metal thickness should be at least five times of the skin depth five delta AS. It's sufficient to design any printed lines.

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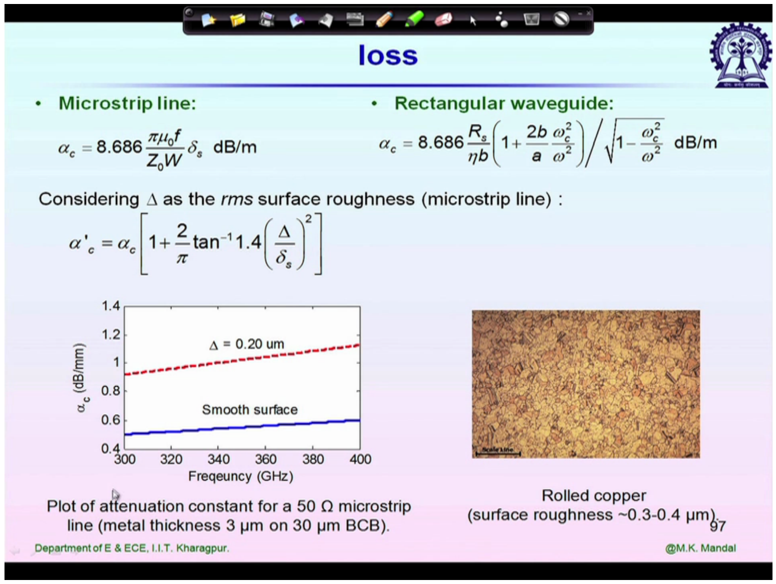

So for this example you see we are considering 300 gigahertz to 400 gigahertz and we consider three micrometre thickness of strip and ground plane. So that is more than enough for this frequency range. You can compare this value with rectangular waveguide alpha C it is also a function of frequency but at cut off its infinity but how we define the operating band of a rectangular waveguide.

It is 1.25 times FC to 1.9 times of FC where the loss alpha C it will be much less compare to microstrip line. How small? Even 10 to 20 times smaller so that's why at sub millimetre wave frequency or even at millimetre wave frequencies we can't use microstrip line for long distance communication.

Then what we do? We use this printed lines like microstrip lines or CPW line as interconnect for chip to chip connections or from one component to another component connection which will be needing to design any millimetre wave circuits. So let's take a short break then we will start again. Thank you!