Millimeter Wave Technology.
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Lecture-06.
Guiding Structures

Okay so today we are going to see what are the different sources of losses?

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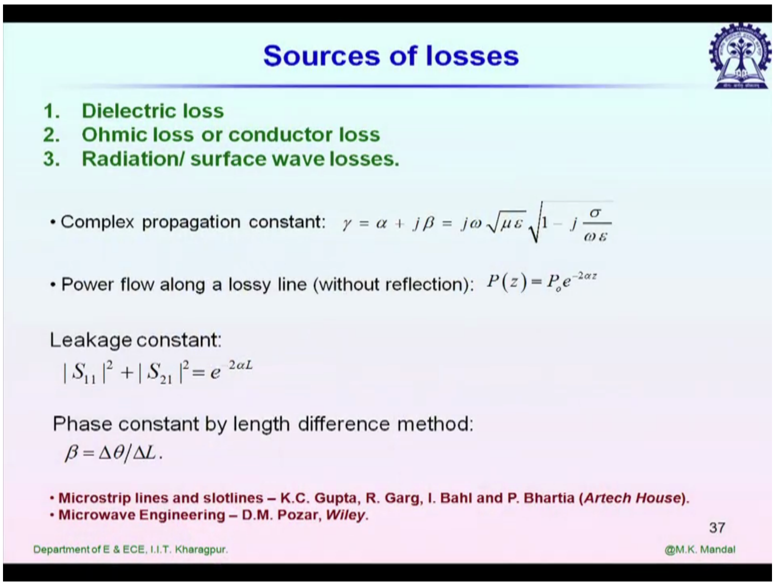

So whenever we design any components or circuit at millimetre wave frequency so we have to be very careful about the losses and mono mode bandwidth. So this mono mode bandwidth will see later. How we define and what is it? So let us start with what are the sources of losses? So last day we have seen that if we have a transmission line which supports TEM wave so in that case the propagation on stand it becomes a complex quantity.

Gama this is equal to alpha plus J beta and if we can determine the scattering parameter is H11 and H21 of a given guiding structure so in that case we can calculate alpha the attenuation constant and beta the phase constant of a any given guiding structure. So now let us see what are the sources of losses?

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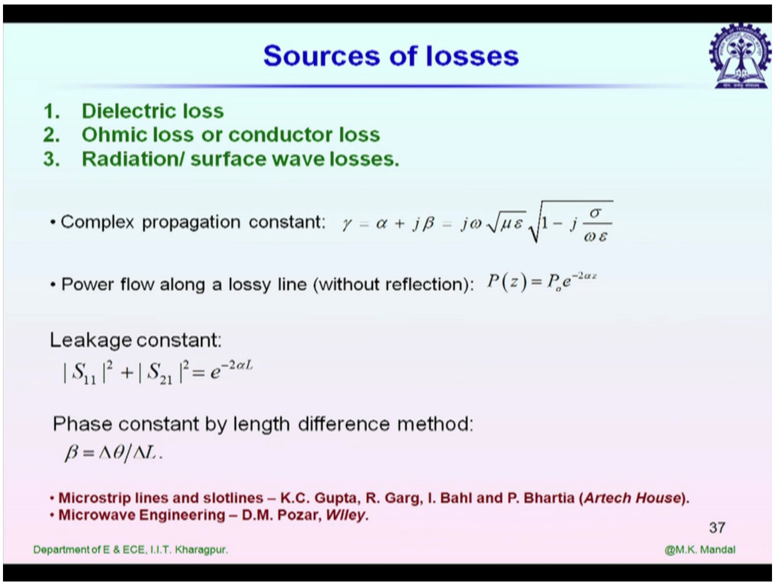

So we have mainly 3 different sources of losses dielectric loss, conductor loss and the radiation and surface wave loss.

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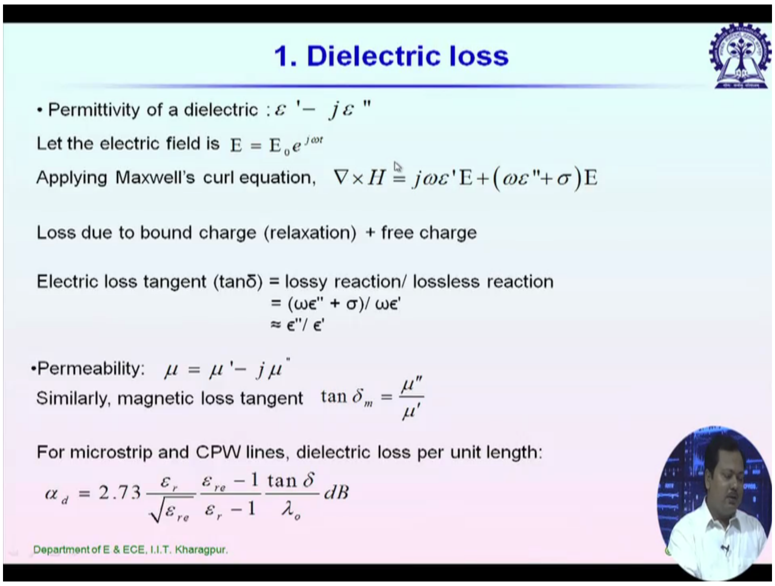

So dielectric loss why it happens? So whenever any electromagnetic wave propagates through any dielectric medium or any insulating medium in that case the molecules of any dielectric layer it behaves as dipole. Now we have thermal noise so due to thermal noise the orientation of this dipoles are in random direction.

So when electromagnetic wave propagates through this medium then this dipole they try to orient itself so in that procedure it absorb some amount of energy so and finally it will give us some heat so its loss to the propagating electromagnetic wave. So how we quantify this loss so instead of the simple dielectric constant epsilon R we represent dielectric constant by a complex number?

So we can see the permittivity in general it has one real component epsilon dash and one imaginary component J epsilon double dash. Intentionally we are using one negative sign here so that loss it becomes a positive quantity. Now let us consider the umm any monochromatic plane wave is propagating through this dielectric medium so in that case if it is linearly polarised so electric field E it can be written as E nought into E to the power J omega T. Now let us use the maxwells curl equation curl H equal to J plus Del T Del T so let us solve it and let us see what happens.

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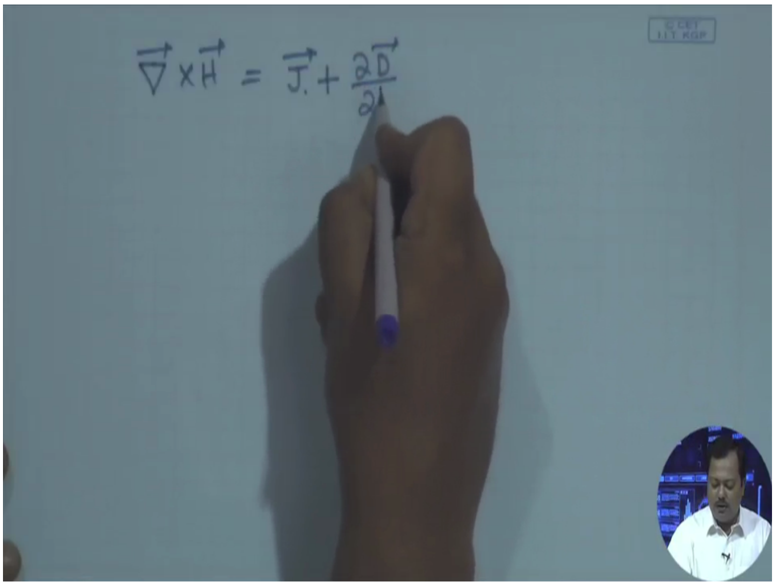

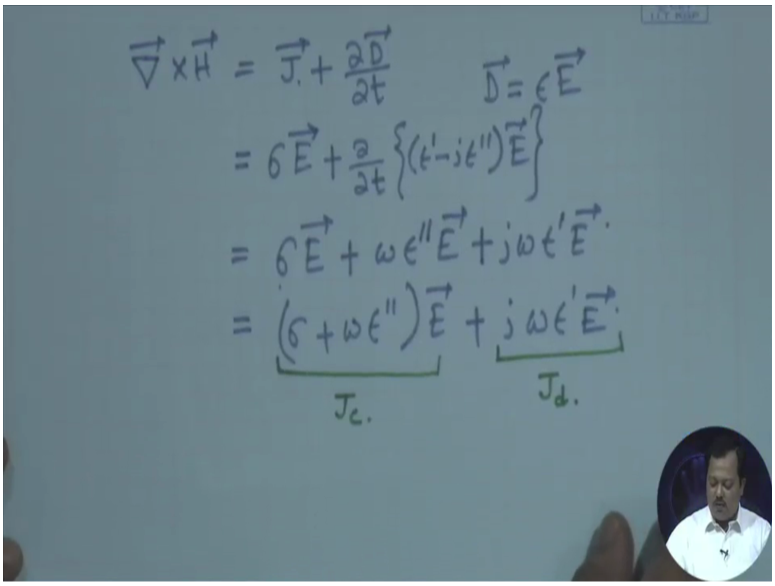

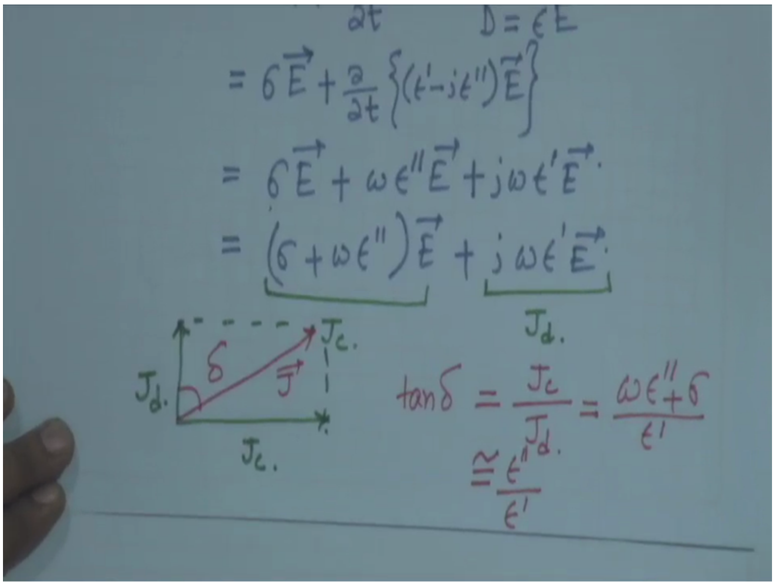

So curl H this is equal to the conduction current component JC plus Del D Del T. D is the displacement factor so this is equal to epsilon E so where epsilon its a complex quantity. It can be given by epsilon dash minus J epsilon double dash. So the conduction current quantity it is related to the applied electric field as sigma into E where sigma is the conductivity of the medium.

So since we are considering a dielectric medium sigma is negligibly small we can also consider sigma as zero so plus del del T of so we have epsilon so epsilon dash minus J epsilon double dash E. So it comes sigma E plus we have omega epsilon double dash E plus the imaginary quantity J omega epsilon dash E. So because of this real quantity sigma we know that this medium will behave as a lossy medium.

Now we see the imaginary quantity epsilon dash so in the final expression it will add up to this real quantity so then together this is sigma plus omega epsilon double dash E and the imaginary quantity we have J omega epsilon dash E. So this first part we can call it the conduction current component JC and the second part we can call it the displacement current component JD.

Now if we represent it using vector diagram then JC it is along the real axis and JD this is along the imaginary axis then the overall current component J it mix and angle with the displacement current component and this angle tan tangent it can be given by JC by JD so or if I put the values it comes omega epsilon double dash plus sigma divided by epsilon dash so this is called the loss tangent of this dielectric material.

Since we are considering dielectric we can assume sigma is zero then this quantity is approximately we can write down epsilon double dash divided by epsilon dash. Now let us go back to our slide.

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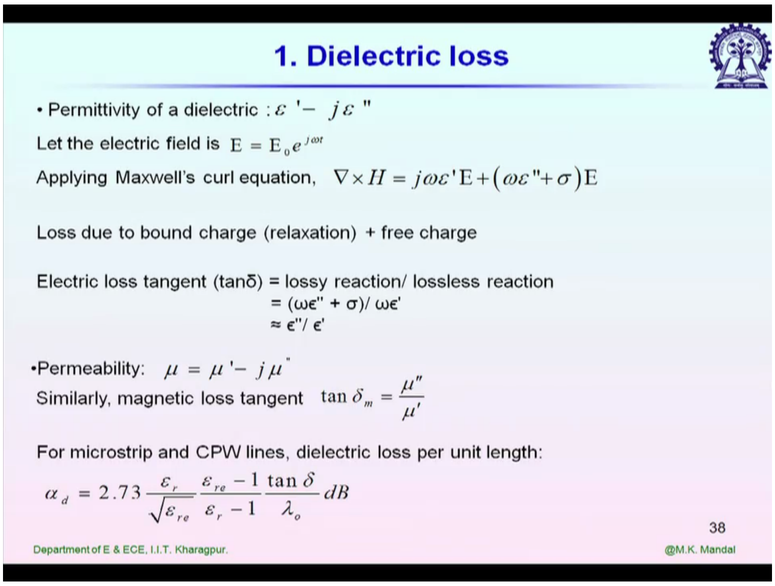

So in general then electric loss tangent tan delta it is define as the lossy reaction by loss less reaction and which we see equal to omega epsilon double dash plus sigma divided by omega epsilon dash. So if I plot loss tangent versus frequency so what you think? It will increase or decrease? so above we have sigma plus omega epsilon double dash so it should decrease with frequency.

But in last lectures we have seen the some major loss tangent values at different frequency so measured value usually we have seen it increases with frequency. So similarly we can define magnetic loss tangent the procedure is very similar and will represent in this case tan delta M this is equal to Mu double dash by Mu dash.

But most of the materials are not magnetically susceptible so we can simply neglect this tan delta M part for umm most of the materials unless we are considering materials like ferrites, iron or nickel. Now if I consider a micro strip line or CPW line so we we have to fabricate them on some dielectric substrate so obviously it will be associated with some dielectric loss we have a closed form expression for that.

So the dielectric loss per unit length for this 2 lines alpha D that is equal to approximately 2.73 multiplied by this factor so it depends on tan delta but as well as frequency because we have one term lambda nought here and if we increase frequency lambda nought it will decrease. So if it decreases as whole alpha D it will increase so we see that for CPW line and micro strip line dielectric loss it increases with frequency as the close form expression says.

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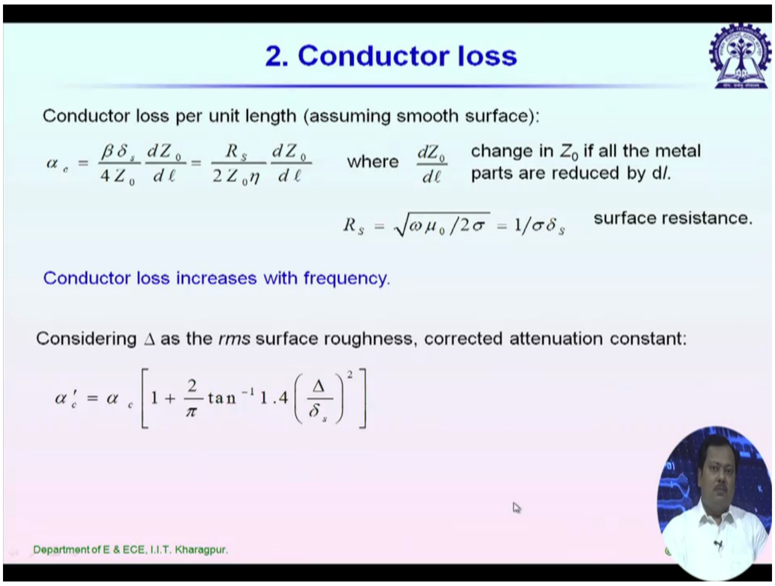

Next is conductor loss that is another important factor so this represent the joule heating now if we have a TEM line so that means a guiding wave guiding structure that is supporting transfers electromagnetic wave so in that case we can actually theoretically calculate what is the attenuation constant due to conductor loss alpha C? So alpha C in this case this is equal to beta into delta S by 4 Z nought into DTL of Z nought.

Z nought this is the characteristics impedance of the transmission line delta S this is the skin depth so we can represent delta S in terms of surface resistance as shown here. RS this is equal to square root of omega Mu not by twice sigma that is equal to1 by sigma delta S and this DTL of Z nought it represents change in Z nought if all the metal parts are reduced by delta L.

So for example if we have a coaxial cable umm let us say its excited in TEM mode so in that case we have to first calculate what is the characteristics impedance of a given coaxial cable and then what we will be doing? So we will reduce inner conductors as well as we will increase the diameter of outer conductor by delta L and we will recalculate what is the new Z nought value.

So that will give you then delta Z nought then we can easily calculate del del or DDL of umm Z nought so we can calculate alpha C for that given coaxial cable. Now when we calculate alpha C using this formula we made one important assumption. What is that assumption?

That the metal surface is smooth so there is no roughness on the metal surface but if we look at practical metal surface it has some roughness due to these roughness loss further increases.

We have again one more close firm expression so umm this is given below. So let us say the surface roughness umm we are defining by umm capital delta and it represents the RMS value of surface roughness. Then the corrected attenuation constant for a rough surface alpha C dash this is equal to alpha C multiplied by 1 plus we have a correction factor here. So 2 by pie tan inverse 1.4 into capital delta by small delta is whole square.

So small delta is this is the skin depth of that metal. So we see then actual alpha C it will be much more compare to what we calculated previously. And it also increases with this capital delta so for a rougher surface then we have more conductor loss.

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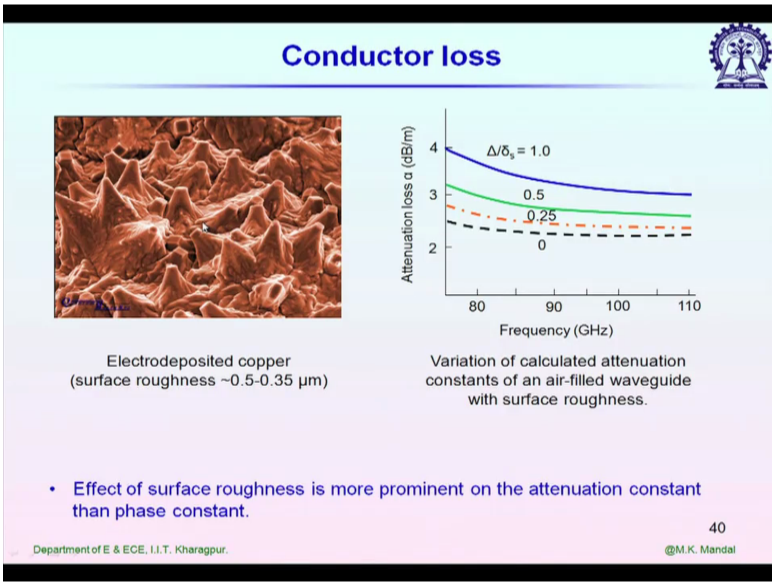

So let us take one example so before that you see in this picture top left picture. So it shows electro deposited copper zoom in view at least 100 times zoom in umm view. So here typical surface roughness is point 5 to point 35 micrometer now you compare these value with the skin depth. Do you remember? What is the skin depth value of our copper at 100 gigahertz? Its point 21 micro meter.

So umm if I compare this value this capital delta its already more than delta S skin depth. So surface roughness will be very high due to the surface roughness we have very high conductor loss than what we calculated. So this type of copper umm is used to umm make that fixed PCB printed circuit board. So if you take a close photograph of any printed circuit board from top you can see the copper is looking like this.

So now it umm when the companies they fabricate this printed circuit boards they follow actually different fabrication procedure so this is for the electro deposited copper we have also rolled copper. So for rolled copper this surface roughness is little smaller. So then another important observation we have that when we are going to order our substrate to design millimetre wave components so in that case we have to also look at the surface roughness value.

So if the surface roughness is very high then we will expecting high conductor loss. So at least you look at the value it should be much smaller compare to the skin depth value. When you choose your substrate so be careful about that.

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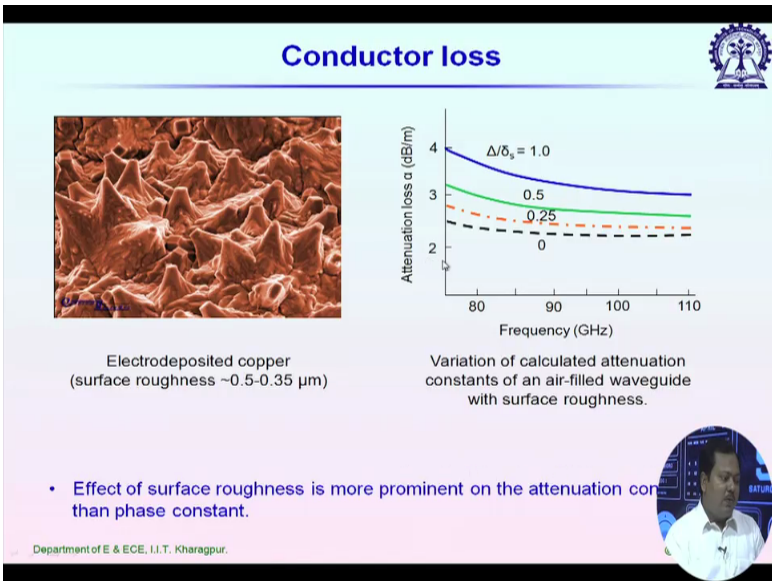

So another example we will take. So here we are what we are doing? We are plotting the attenuation loss alpha this represents the conductor loss only. Versus frequency for a standard rectangular wave guide WR 10. Its air filled so if I consider umm zero surface roughness then this bottom most line it shows the variation of alpha C versus frequency. So typical value is 2.2 to 2.3 DB per meter and now these are all theoretically calculated values.

If I increase delta value let us say point 25 to 1 so this capital delta by small delta S so that means it represents the surface roughness with respect to the skin depth value at the mid band frequency. So we see that alpha C is increasing and at lower end it can be as high as 2 times of the original values.

So the conclusion is then the effect of surface umm roughness umm it changes actually alpha C and now we see in gama we have 2 quantities alpha and beta. So the effect of surface roughness on alpha is more prominent compare to beta.

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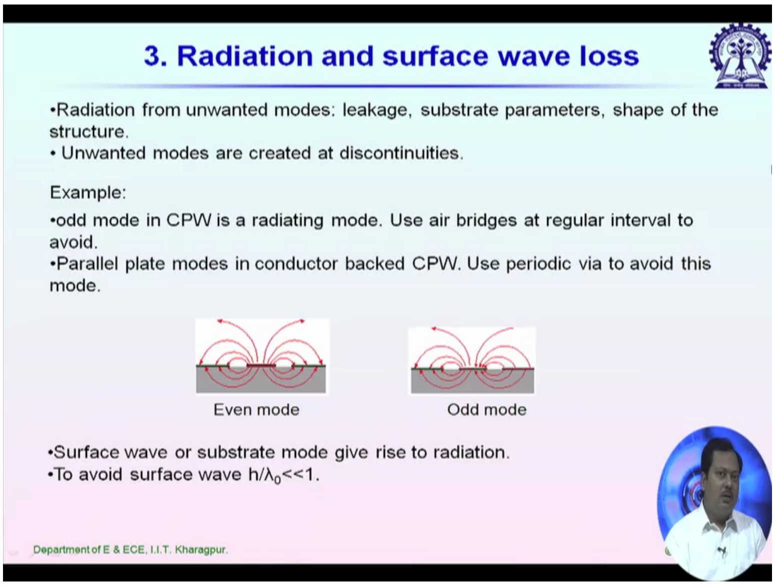

Next is radiation and surface wave loss so whenever we have any discontinuity in this structure let us say we have some open ended staff or any metal dielectric discontinuity or let us say you have dielectric air boundary in your structure or it can be in any form you have some imperious step in your circuit in your semi open structure. For example micro strip imperious step so it will radiate.

Now the amount of radiation obviously depends on the structure and the direction of this radiation is in random direction. So umm now for micro strip line or CPW line always will be having some flinging fields in air. But if we have any flinging field in air that does not necessarily means it will radiate.

Umm the basic condition for radiation is that the electric field and magnetic field component which is in air that should be in phase otherwise if they are in phase coordination we have umm reactive components, reactive power and the energy whatever we have it will be stored in the near field so it will not radiate. So if we have any EM sulphur or full wave simulator we can simulate our structure and actually we can calculate umm the radiation or the amount of radiation coming out from our structure. This is very important from EMI EMC point of view.

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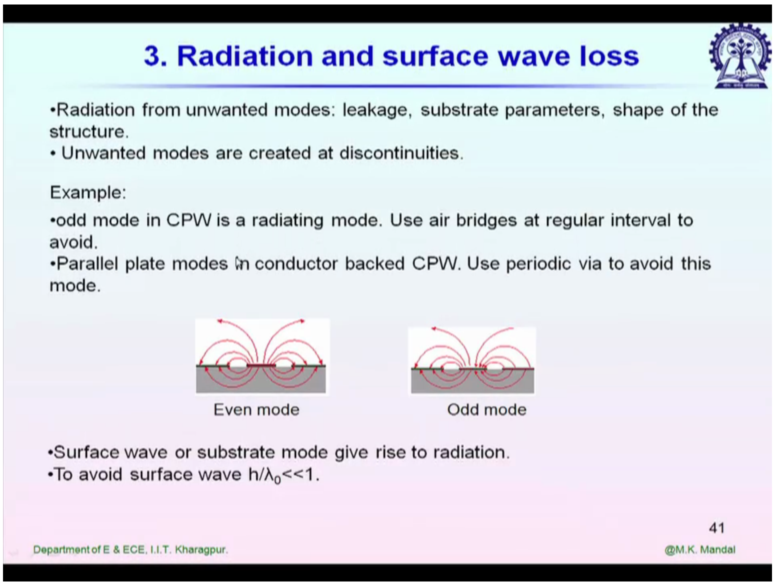

So next one more example, if any transmission line or any other guiding structure if it supports fast wave it is associated with radiation and we lastly discussed that umm the structure it will radiate continuously along its length. So let us take one example so this figure it shows a CPW line so this is the cross section of the CPW line so we have three strips these are sitting on a dielectric slab.

So this is the central strip and left and right most strip they are used as the ground length. Now this configuration it can be excited in even mode as well as it can be excited in odd mode. So in even mode if you look at the electric field plot they start from the signal line or the central line and terminates at ground length so we can say that both of this ground left hand and right hand side strip they are at same potential.

Now look at the right figure so this CPW line is excited in odd mode now the electric field line they starts from the right most crown and then again from signal to left crown so that means the right most crown it is at higher potential compare to the left most crown. And in practice even mode its a slow wave and its a guided umm component umm the guided mode.

So the desired mode is even mode and odd mode it will be radiated continuously along the line so it is undesired mode. So what can be the remedy? We don’t want this odd mode so if I look at this two figures one important observation is that for even mode two ground planes they are at same potential and in odd mode this two ground planes they are at different potential. So practically what we do?

We use bonding wire simply copper wire and that is soldered between the two extreme ground planes. Now if I solder one copper wire between this two extreme ground planes so we make it sure that two ground planes they are at same potential. So we are forcing it by using external copper wire. So that is a way how we can suppress odd mode excitation of CPW line.

So we have to use this copper wire in periodic nature so umm the periodicity it should be less than lambda g by 4 where lambda g is the guided wave length in CPW line. So next we will see that substrate a dielectric slab simply it can support wave propagation and the problem with this type of wave propagation is that this is not just confined to any one particular channel it will spray it throughout the substrate.

And we call these as the substrate modes or the surface wave mode. And this electro umm this type of transmission line CPW and micro strip line they are fabricated on a dielectric slab. So they can easily excite the surface wave mode and what is the problem of surface wave mode? Since it spread throughout the substrate so we will be having a electromagnetic interference problem with the near by circuit or (())(18:07) problem.

And the power loss to the surface wave so its a wastage to the transmission line because we cannot utilize this power so then the surface wave particularly at very high frequency like at millimetre wave frequency the effect is detrimental and we have to study its effect very carefully so that we can avoid it.

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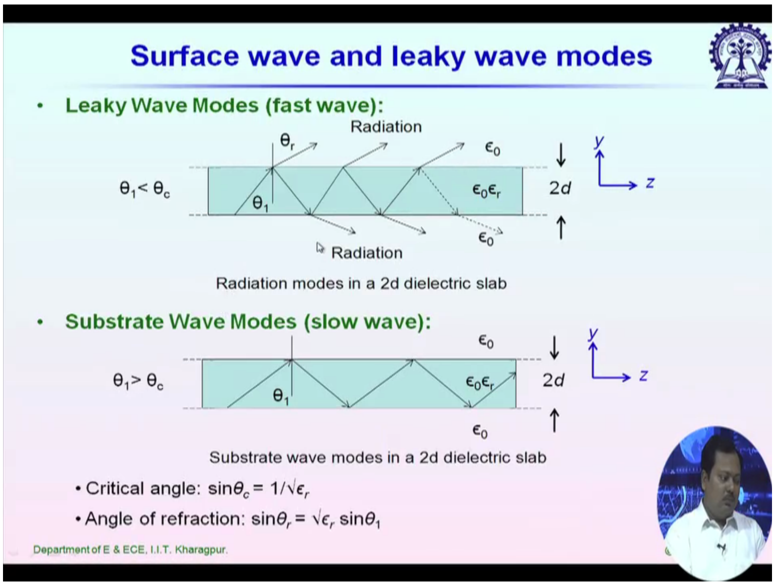

So before starting the surface wave mode in general let us discuss about what are leaky wave modes? And what are substrate wave modes which are confined to the substrate? Let us say we have a dielectric slab as shown in this figure and any wave somehow incident inside this dielectric and this is incident on the dielectric air boundary with angle of incidents theta 1.

Now if this angle of incidents is smaller than the critical angle then a part of this incident wave it will be um transmitted to air and another part is reflected back inside dielectric. And this this it will continue throughout the substrate. So as a whole whatever this refracted components of transmitted component it comes out as radiation from the structure and we call it the leaky wave mode it can be shown mathematically.

It is possible only if the phase velocity of this wave is higher than C nought so that means in the case of a fast wave so this is a conceptual diagram. Next the same wave but in this case angle of incident is more than the critical angle so the relationship for critical angle sin theta C this is equal to 1 by root of epsilon R epsilon R is the dielectric constant of the slab. Now since theta 1 is more than theta C whole of this incident electromagnetic wave is reflected back.

So we have 2 total reflections and it will continue. So we see that a dielectric slab itself it can behave as a guiding structure and in this case mathematically it can be shown VP is less than C that means its a slow wave scenario and we don't have any significannot radiation from this structure. So in this case umm electromagnetic wave propagates through the dielectric slab but what is the problem then?

The problem is that it not only propagate in Z direction since the dielectric slab it is in XZ plane so it will propagate in XZ plane and it will spread throughout the substrate so we cannot utilize this substrate wave mode or surface wave mode. So let us learn about the surface wave mode in details.

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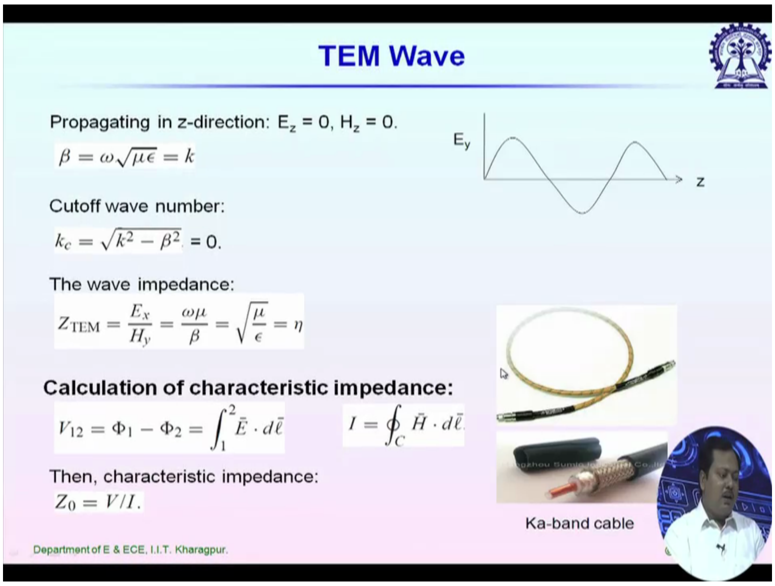

So before that we need to know what are the different types of modes that can exist in any guiding structure. So mainly we deal with 3 modes TEM mode or transfers electromagnetic mode so by definition in the direction of propagation it does not have any electric field or magnetic filled component then we have transfers electric mode.

In the direction of propagation we will not have any electric field component and the third one is transfers magnetic mode. In addition to these we have many hybrid modes so right now we are not discussing those modes. So mainly we will deal with these 3 modes. So the let us first learn what are the characteristics of these 3 different modes. So let us start with the TEM mode.

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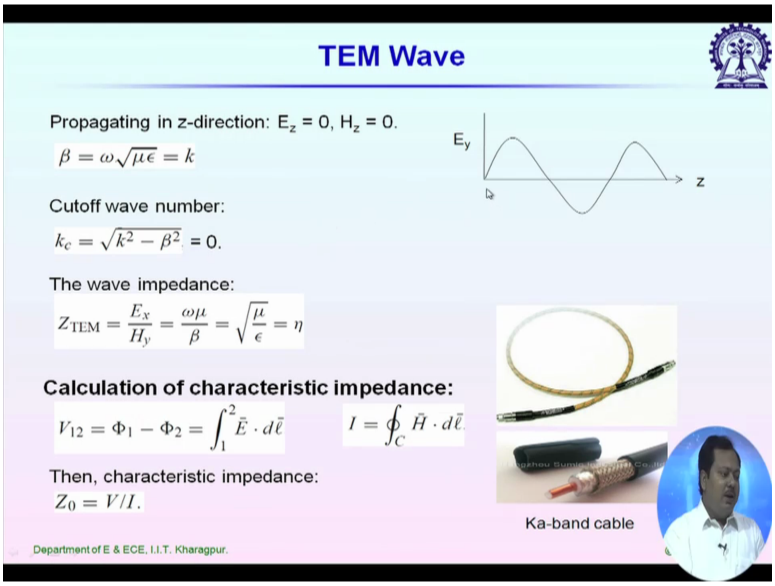

So we are considering a electromagnetic wave is propagating in Z direction and its linearly polarized it has EY components so by definition then EZ equal to zero and HZ equal to zero and beta it can be given as omega square root of Mu epsilon that is equal to K and cut off wave number KC this is equal to square root of K square minus beta square this is equal to zero. So it is interesting to know that KC cutoff wave number is zero.

So that means it does not have any cutoff frequency. So it can start propagation right from DC. The wave impedance Z for TEM line its how we define. EX by HY this is equal to square root of Mu by Epsilon some time we call it eta. For TEM line we can calculate the characteristic impedance since we can calculate the voltage and current voltage. So how we calculate current and voltage let us say we have a 2 wire transmission line system let me draw one diagram.

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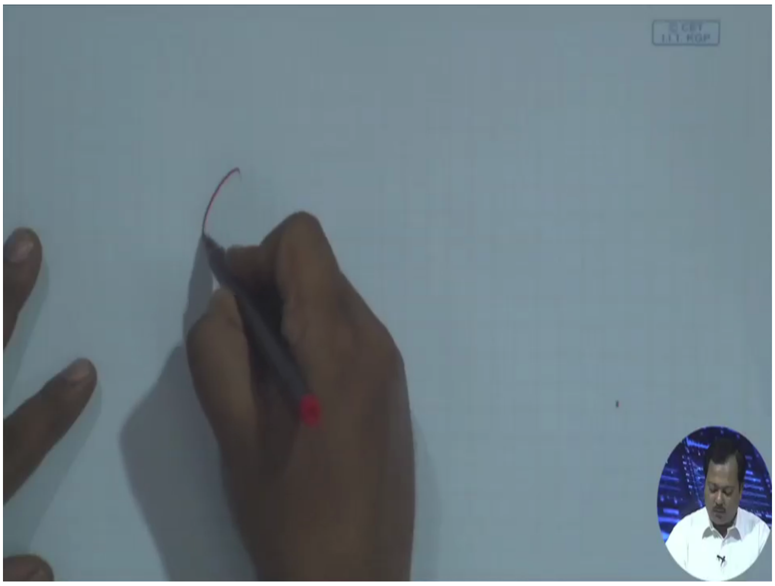

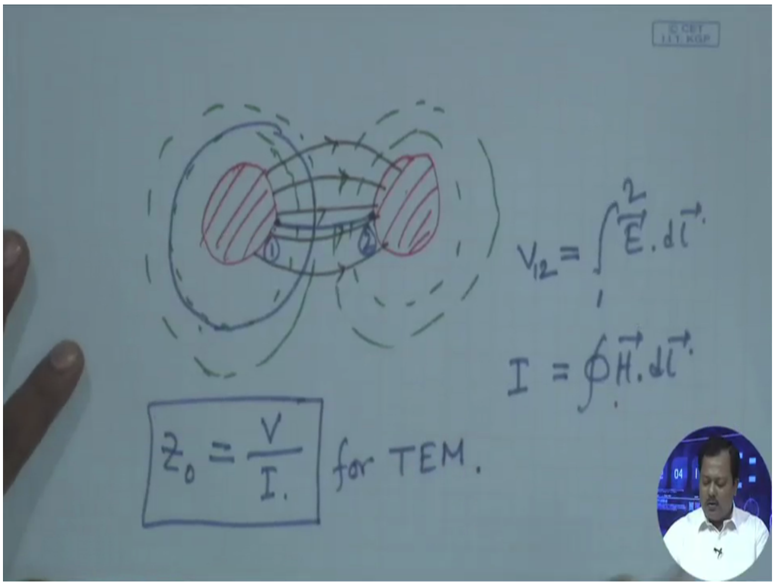

So if I draw the electric filed components this is the electric field lines and the magnetic field lines it will be perpendicular to it and it will in circle the conductor. So this red part it shows the conductor it can be of any shape. So we see that electric field its start from a conductor and it terminates in another conductor and how to calculate the potential difference between this two? So in that case we have to just one line let us say from point 1 to point 2.

So then what we do V12 this is equal to integration 1 to 2 E dot DL. So this will give you the potential difference between this 2 or voltage difference. Now how we can calculate current flowing through any single conductor we have to consider one closed loop and then the current component I this is equal to closed integral H dot DL.

So we see that the electric field it should starts at some point and it should terminate at some point so so that a potential difference can exist between this 2. So at least it will be a 2 conductor system or more than that otherwise it cannot support TEM or transfers electromagnetic wave and in this case since we can calculate voltage and current then we can easily define characteristic impedance of the line that is equal to V by I so this is only possible for TEM line. So now we will take a short break and then we will continue with other different modes.