Millimeter Wave Technology.
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Lecture-07.
Guiding Structures (Contd.)

Okay so welcome back. Let us take one example of a line which supports TEM. There are many examples one of them is coaxial cable.

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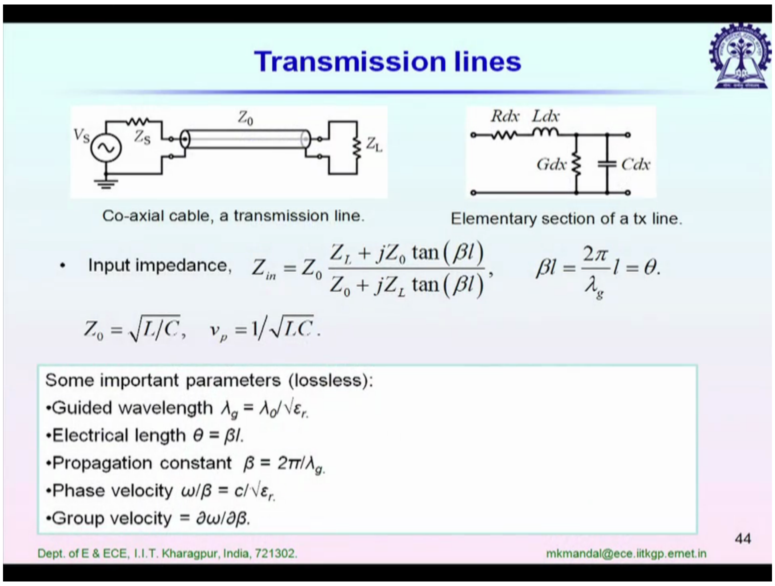

One coaxial cable it can support TEM as well as TE and TM wave but since TEM it does not have any cut off frequency it will appear first an if we keep on increasing the operating frequency so first transfers electromagnetic mode will appear and then transfers magnetic mode will appear so we are talking about mono mode bandwidth operation we will see the electric and magnetic field orientation is different for this three different lines.

And in practical design we can only deal with one single mode. So that why it is always preferred that for a given transmission line or guiding structure we will be using the fundamental mode. So for coaxial cable its TEM wave TEM mode.

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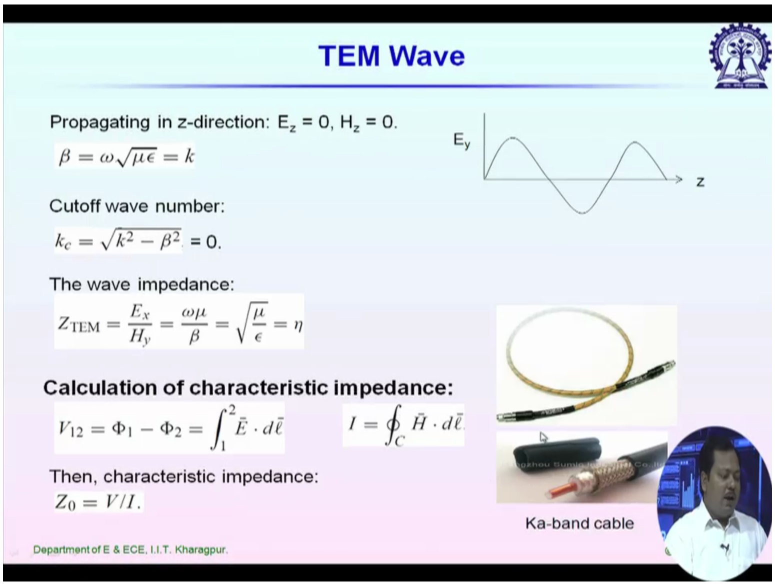

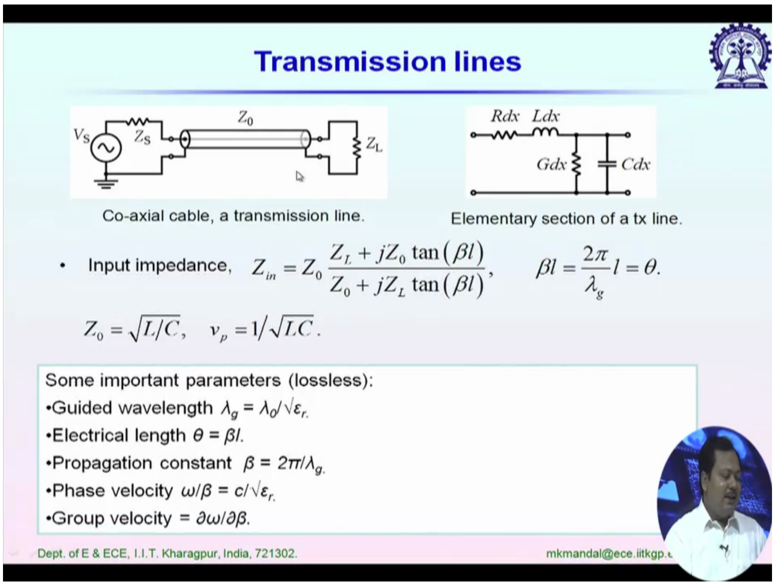

So let us take one example here so its shows the coaxial cable it comes in different forms it very popular at microwave frequency at millimetre wave frequency it becomes lossy but since it has the advantage that we can easily turn it and also twist it. It is usually used with the measuring instrument so this transfers electromagnetic wave any guiding structure that is supporting it can be represented by a transmission line.

Its a two wire line so for this one then we can easily calculate what is the input impedance of the line what is beta and what is alpha of this transmission line. Let us consider the scenario a coaxial cable it is connected to 1 millimetre wave source which is represented by the voltage source and its internal impedance ZS and it is terminated by load complex load.

Its given by Z L so in that case the input impedance Zin as seen by the source that is equal to Z nought into ZL plus JZ nought tan beta L. So this beta L this is nothing but electrical length of this line theta divided by we have again Z nought plus JZ L tan beta L. So the input impedance its function of ZL and Z nought as well as its a function of beta L theta so if we keep everything fixed.

And then we change the frequency operating frequency then the input impedance will change. Since its a function of beta beta is equal to twice pie by lambda g. So sometimes we will see that we use distributed firms like this one using resistor, inductor, con um conductance and capacitor. And we represent a transmission line but what is the difference between the left figure and right figure is that this right figure it cant predict periodicity of a transmission line.

Anyway whenever we have a transmission line like this then for the this one we have some closed form expression for example the guided wave length lambda G this is approximately lambda nought by root epsilon R. Electrical length already we have seen theta is equal to beta into L. And propagation constant beta equal to twice pie by lambda G. Phase velocity omega by beta and group velocity del del beta of omega.

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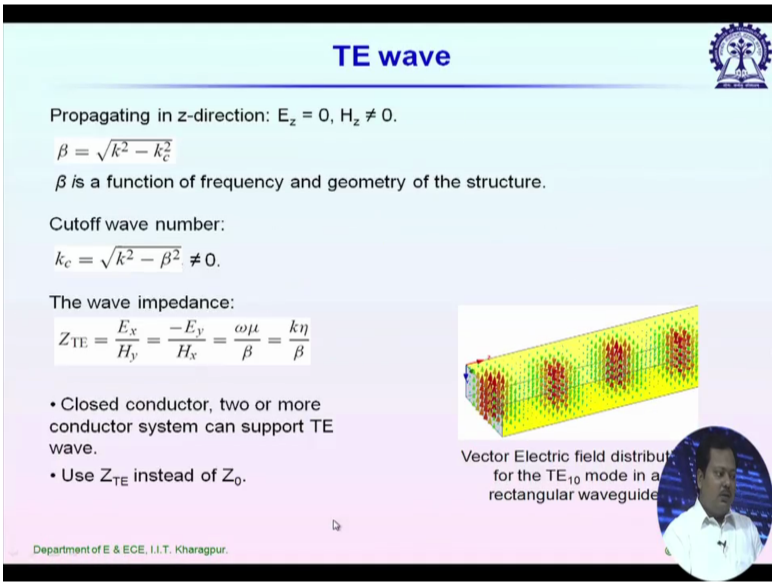

So next is TE wave 1 popular guiding structure that supports TE wave is rectangular wave guide. So in this case by definition EZ equal to zero since we are considering propagation in Z direction and HZ that not equal to zero. And beta this is equal to root of K square minus

KC square. So we have a cut off wave number here that can be given by square root of K square minus beta square and which is not equal to zero.

So it cant support DC it has a cut off frequency and it will support electromagnetic wave propagation only above that cut off frequency in this case we cant calculate voltage or current directly and we cant define the characteristics impedance of the line Z nought but we use another term which is called the wave impedance ZTE for TE wave it is again EX by HY and it comes omega Mu by beta or K eta by beta. Usually a closed conductor and not only that two or more conductor system also can support TE wave.

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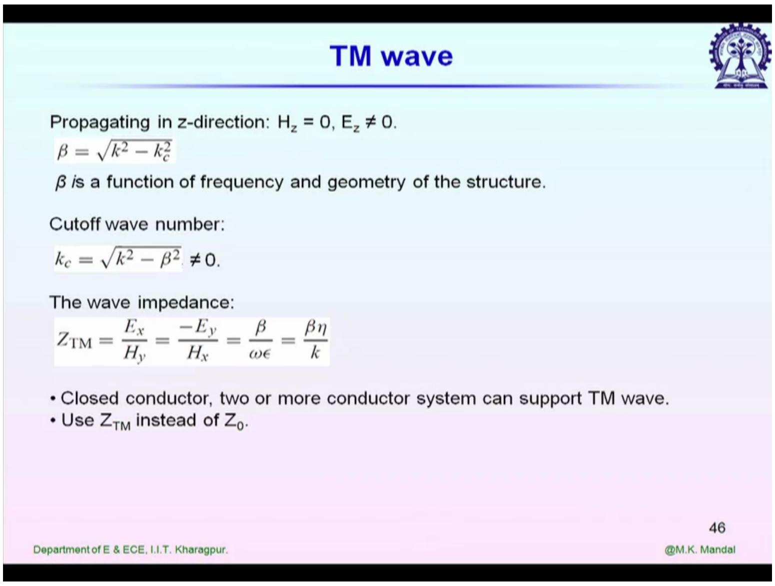

Next is TM wave it also have similar property like TE but in this case HZ is equal to zero and EZ is not equal to zero. And the cut off wave number KC this is equal to square root of K square minus beta square so just like TE wave in this case also we have a cut or frequency and wave propagation starts above cut of frequency and the wave impedance is define as ZTM equal to EX by Hy that is equal to Beta by omega epsilon or Beta into eta by K.

So again closed conductor 2 or more conductor system can support TM wave. And we cant define characteristic impedance for TM wave as well.

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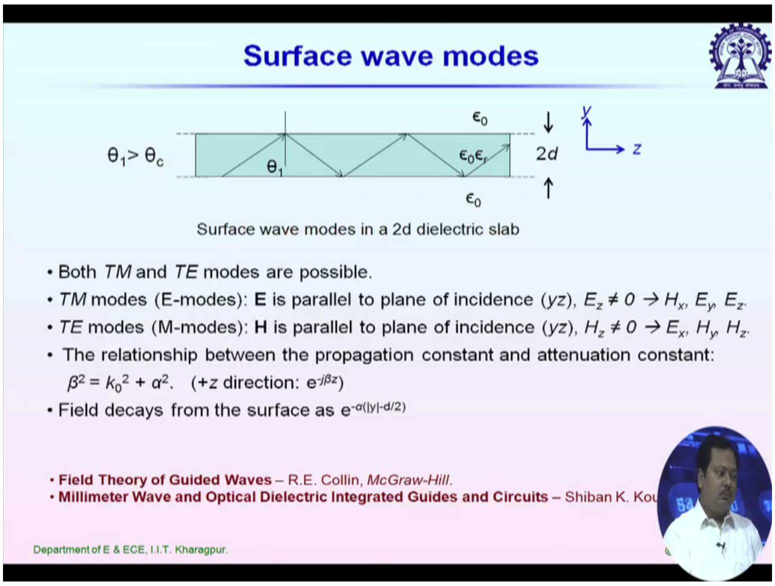

So next let us see what is surface wave? And what are the problems we face due to surface wave? So let us start with the dielectric slab we are considering wave propagation in Z direction and this dielectric slab its infinite in X Z direction so Y is the perpendicular direction. We are considering origin at the centre of this dielectric medium it can be shown it can support TM and TE modes.

But not TEM mode since we don't have 2 conductor at least 2 conductor so TM mode sometimes also known as the E modes in this case the electric field is parallel to plane of incidence. So if I consider this diagram so electric field its incident at the dielectric air boundary and the plane of incidence is YZ and then according to definition for the electric field we have only UI and EZ component since E is parallel to this plane.

And since its a TM mode transfers magnetic so in Z direction we don't have any H component so then the dominant electric field component electric and magnetic field components are HX, EY and EZ. Similarly for transverse electric case sometimes we also call it M modes. In this case H is parallel to plane of incidence or YZ so HZ is not equal to zero.

And we have HY and HZ component and as well as the EX component so the relationship between the propagation constant and attenuation constant can be given as beta square is equal to K square K nought square plus alpha square in Z direction and field decays from the surface as E to the power minus alpha y minus D by 2.

So mostly the electric or magnetic field components it will be inside the dielectric if we go above this dielectric inside air or if we consider below this dielectric electric field or magnetic field component they decays exponentially. Let us so let us first consider the TM mode so for TM mode as we have seen from this electric field is parallel to plane of incidence.

For TM mode again we may have 2 different scenarios in one case the Z equal to zero at Y equal to zero and with this the variation of HX with respect to Y that is also equal to zero. We call it symmetric mode and if we solve for the field components let us consider the magnetic field since we have only one magnetic field components in this case sorry.

HX this is equal to A sec of PD Cos Pi Py this is inside the dielectric and outside the dielectric it varies exponentially as we observe it previously and for the anti symmetric mode HX component is zero at Y equal to zero so Y equal to zero means this dotted plane or the ZX plane so on this plane for anti symmetric mode HX equal to zero.

And not only that variation of UI with respect Z that is also equal to zero and in that case HX above and below the dielectric it decreases exponentially and inside dielectric we have a sinusoidal variation with Y.

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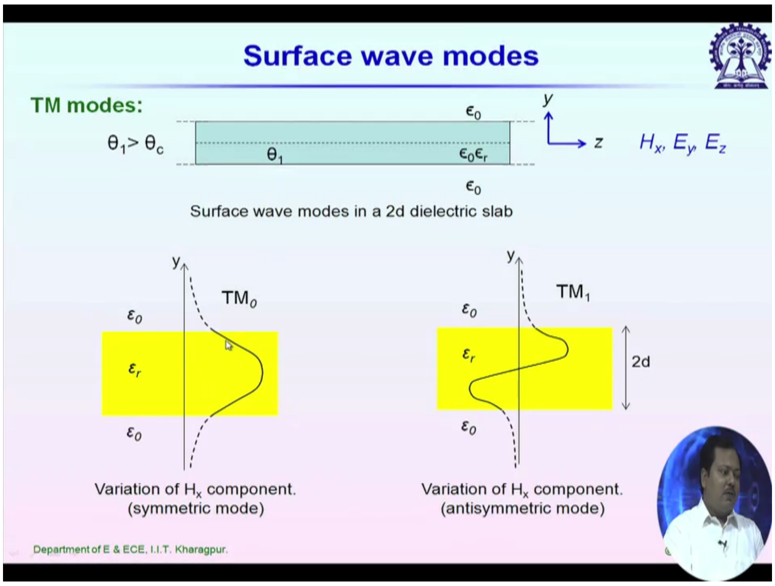

Let us consider the first two modes. The first Symmetric modes that is called TM 01 mode it does not have any cut off frequency this is very interesting. So we are plotting variation of HX with respect to Y. So we see that inside the dielectric slab on the mid plane that is ZX plane HX has maximum component and in air it decays exponentially.

And right side this is the first anti symmetric mode we call it TM 1 mode so as expected on ZX plane HX is equal to zero and inside air again it decays exponentially.

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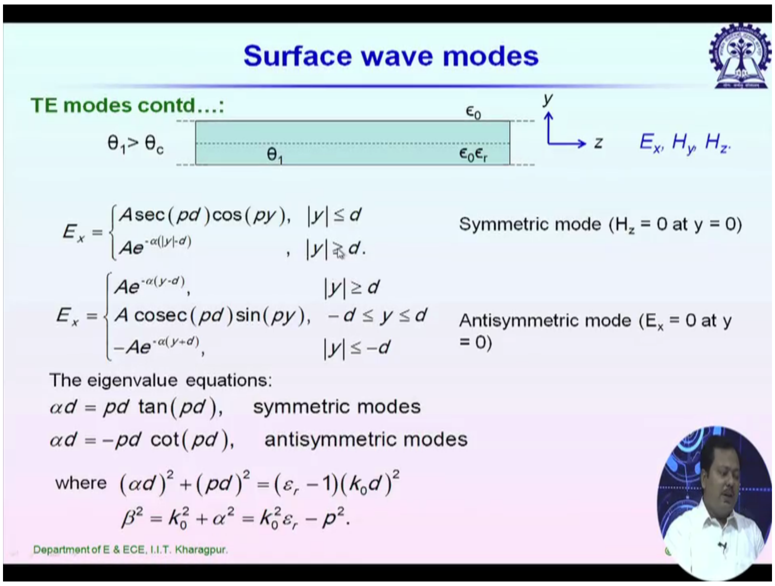

So for the TE modes we can also solve similarly and we also have symmetric modes and anti symmetric modes for symmetric mode HZ is equal to zero at Y equal to zero on this plane. And for anti symmetric mode ex equal to zero at this plane and we have similar variation of electric field component EX like the HX variation of TM mode.

If you look at the values EX equal to this is given its a having a cosinal function of Y inside the dielectric and it decays exponentially outside dielectric similarly for the anti symmetric mode also only thing is that it has a sinusoidal variation inside dielectric so at Y equal to zero we are expecting EX equal to zero

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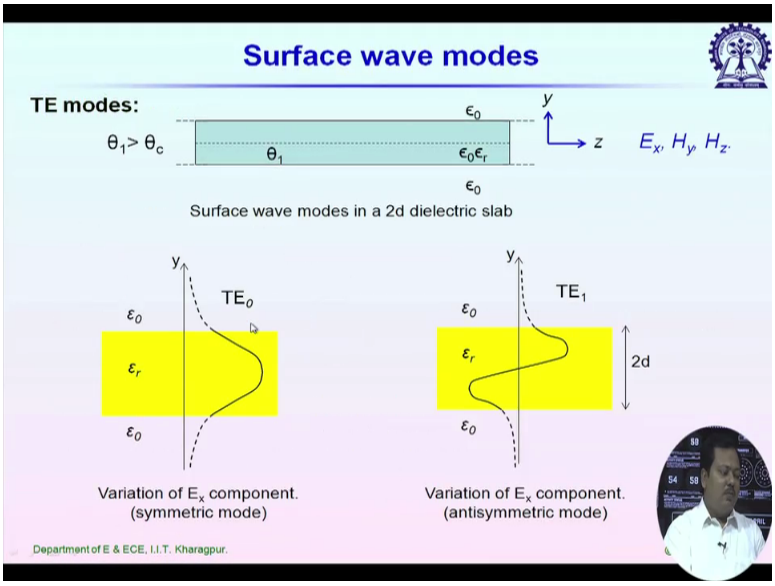

Let us see the plot. So it looks very similar to HX variation of TM mode. So for TE 0 mode again we don't have any cut off frequency for TE 0 mode so in this case the field component EX is maximum on ZX plane and it decays above and below and inside air it decays exponentially look at the first anti symmetric mode of EX on ZX plane again EX is zero and in in air it decays exponentially.

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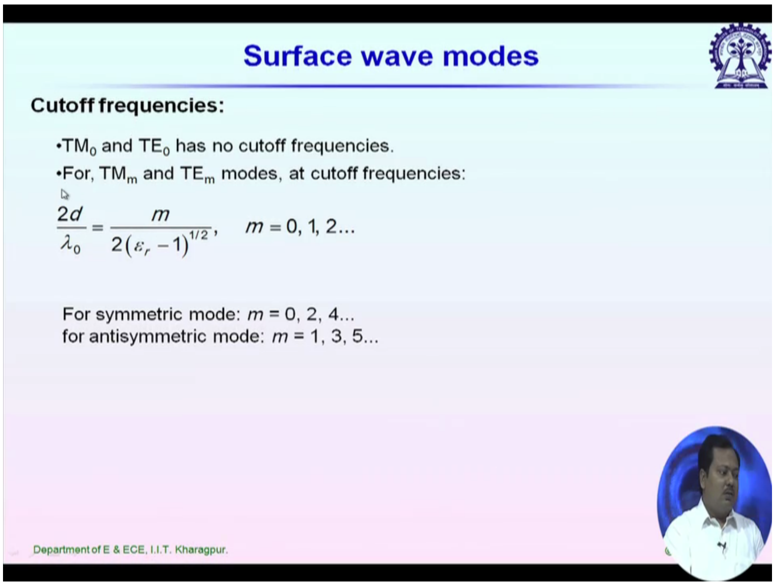

So the cut off frequency some characteristics are described here TM 0 mode and TE 0 mode they have no cut off frequencies. For other modes the cut off frequency can be solved from here twice D by lambda nought lambda nought is the wavelength in free space this is equal to M by 2 into square root of epsilon R minus 1.

Where epsilon R represents the dielectric constant of the slab then for symmetric mode M equal to 0 or any even number and for anti symmetric mode M equal to odd number so from this then we can calculate the cut off frequency for TM 1 TM 2 TM 3 as well as TE1, TE2, TE3 all different modes. So remember TM 0 and TE 0 mode they have no cut off frequency.

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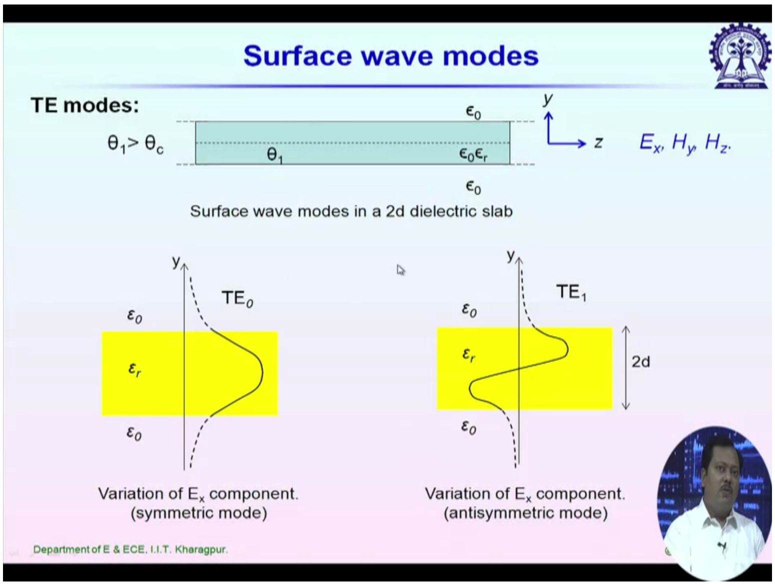

So why we are discussing about the surface wave modes for a dielectric slab? So we can design actually dielectric channel which are popular as guiding structure at millimetre wave frequencies like image guide insular image guide and some other from like non radiating dielectric energy guide we will see later.

So for that the concept of the surface wave modes is very important we will be using this concept to see how those dielectric guides they support electromagnetic wave propagation.

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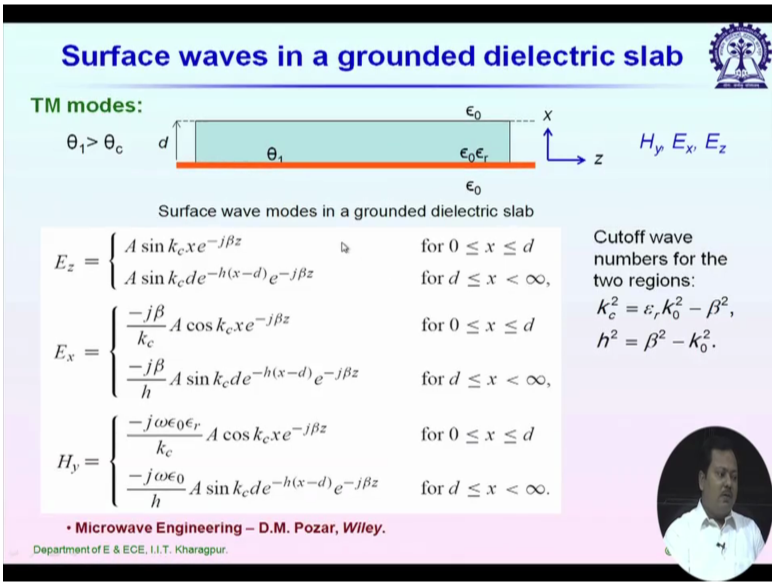

So next we consider another scenario in this case dielectric slab it is placed on a conductor ground plane. Again the wave propagation in Z direction but the perpendicular direction is X here. Let us go directly to the solution it can be shown that this dielectric slab back by a ground plane. It can support TE mode as well as TM mode so we will see T for TE and TM again we have TE0 and TM0 mode and this two modes does not have any cut off frequency.

And it creates lot of problem for any printed circuit board lines. For example if we fabricate a micro strip line or a coplanar wave guide and in any printed circuit board technology so micro strip we have a straight over a dielectric slab and below we have ground so we will be facing a similar problem just like these what we are going to discuss here similarly for the CPW line.

The CPW line it sits over a dielectric slab and usually the ground planes its infinite. So again it is somewhat similar to this problem. Also we have conductor back CPW line in that case we use a ground plane another second ground plane in addition to top layer CPW line. So let us see them what problem we face for the surface wave in a grounded back directory.

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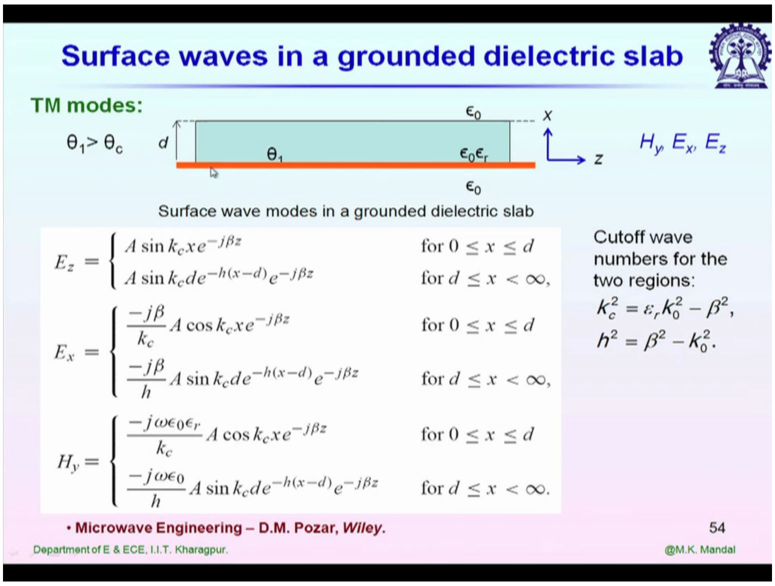

So the first one is TM modes so the electric dominant electric and magnetic field components are EZ HX and Hy if you look at the solution for EZ component EZ component its in which direction? It is in the direction of electromagnetic wave propagation so EZ we have a metal here as the ground plane so its parallel to this metal plane and now from the boundary condition what we have seen?

We have seen that there cant be any tangential electric field component on metal. So without going to the ex final expression we can we can expect or estimate that there wont be there should not be any EZ component for at X is equal to zero. Now let us go to the solution so inside dielectric X equal to 0 to D so you note down that we change the direction of X its perpendicular to ground plane.

So inside dielectric we have sinusoidal variation of EZ component so at X equal to 0 it is 0. And then it increases it becomes maximum at the dielectric air interface and once in a year you see it decreases exponentially so from D for X for more than D it decreases exponentially. Similarly at the EX component EX component it is perpendicular to ground plane right.

So on the ground plane it may have maximum value and look at the expression it has Cosinusoidal variation. So at X equal to 0 its having maximum value and then it decreases with increasing X. And inside air just above this dielectric it decreases exponentially.

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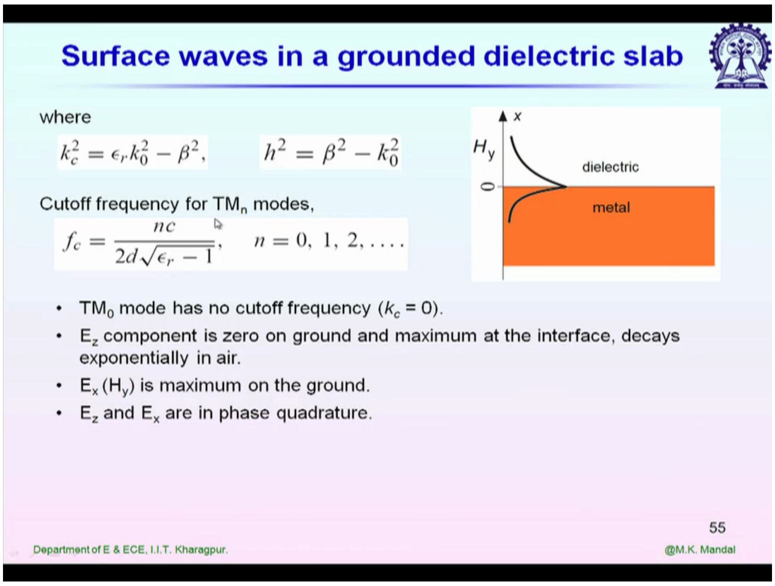

For TM 0 mode we don't have any cut off frequency it can start right from DC but other modes we have the cut off frequency FC this is equal to NC divided by twice D square root of epsilon R minus 1. This is the thickness of the dielectric layer so it depends on the thickness of dielectric layer as well as epsilon R of the dielectric.

And for TM 0 mode you remember it has no cut off frequency for other modes then we can calculate it from here. Now this TM 0 mode it has detrimental effect for micro strip line. Why?

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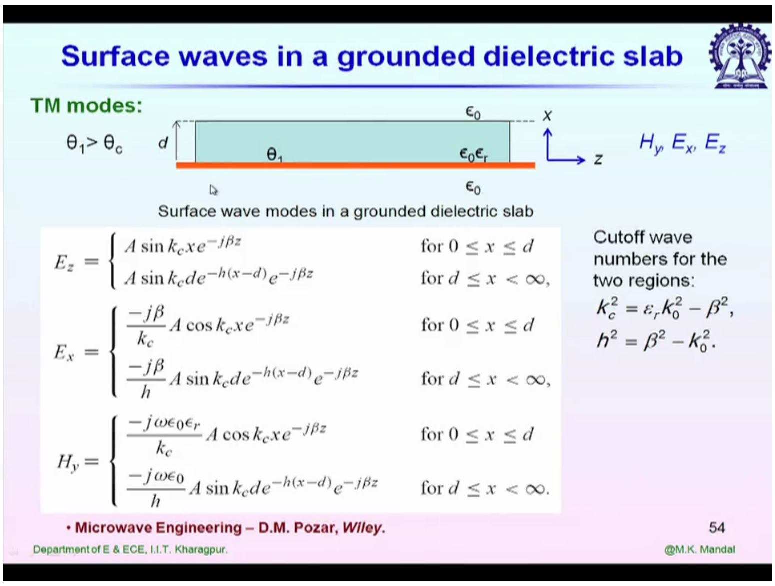

Let us us take first one example. So if I plot the electric field of a micro strip line.

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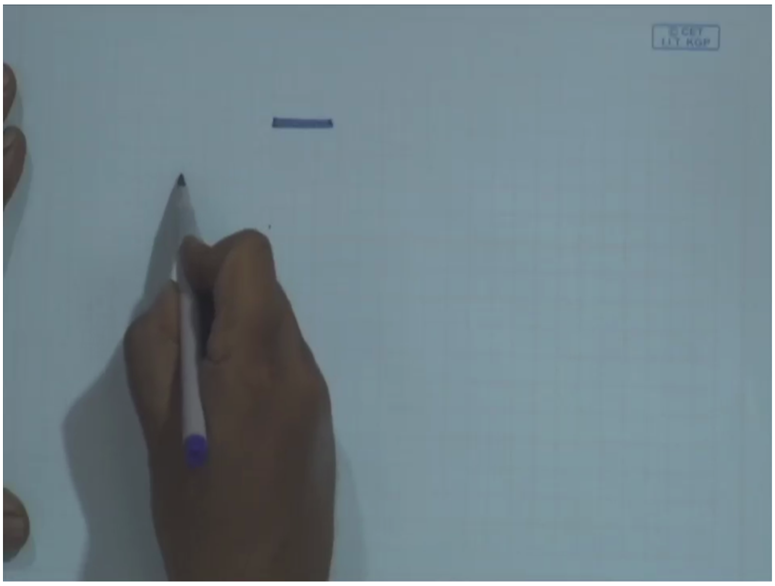

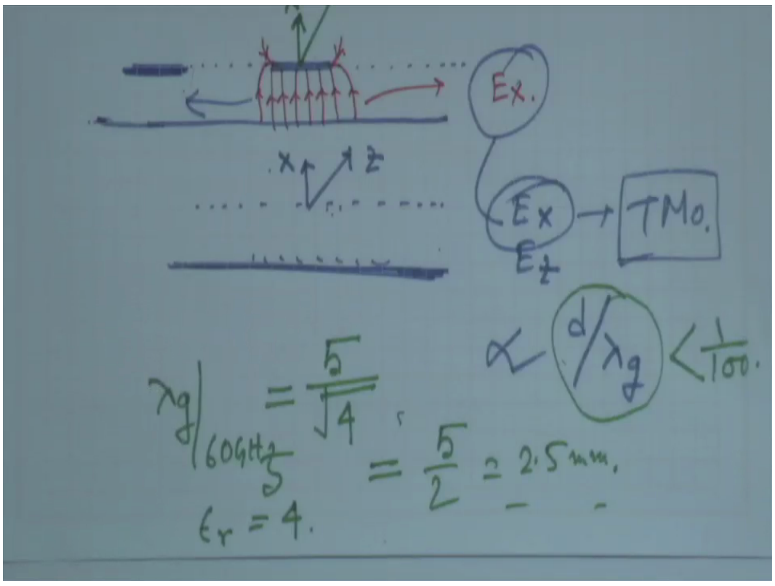

How it looks? Let us say this is the top strip and this is the ground plane. So I am drawing the cross sectional view of a micro strip line and now what we consider for the grounded dielectric slab problem. Perpendicular direction is X direction and the wave propagation direction this is Z direction if I look at the electric fields it will be perpendicular to both strips and the ground. We have also some flinging field components here.

So we see that for micro strip line dominant component of electric field is EX component now for a grounded dielectric slab what we have seen? For a grounded dielectric slab if I consider again the cross sectional view so perpendicular direction is X wave propagation direction is Z so in this case the dominant electric field components are EX and EZ components.

So EX this is maximum on the ground length and EZ component this is maximum at the interface since we have EX component for the micro strip line as well so this micro strip line field component it can easily excite the surface wave. We have a field coupling from the EX to EX and this micro strip line it can easily excite the surface wave so in fact it micro strip line always excites these surface wave which is given as TM 0 mode which has no cut off frequency.

And the power loss to the surface wave it actually increases its a function of thickness with respect to lambda or lambda g. So the amount of power that is loss to this TM 0 mode excitation it is directly proportional to D by lambda g so higher is the thickness of your substrate higher will be power loss to the surface wave mode.

Now at millimetre wave frequency lambda g is very small already we have seen that typically at 60 gigahertz if I calculate lambda g at 60 gigahertz this is equal to let us consider a typical substrate with epsilon R let us say this is equal to 4 then lambda g is 5 divided by square root of epsilon R. So its coming how much? 5 divided by 2 2.5 millimetre lambda g. We can neglect the effect of surface wave only if D by lambda g is more than 1 by 100.

So what you expect? Even if I consider a 10 mil or 20 mil thick substrate we cant neglect the effect of surface wave at millimetre wave frequency. And the problem of surface wave is that not only power not only the power loss but also crosstalk between two side by side lines. So if I have one more micro strip line here it is carrying let us say another signal so we will be having coupling through the surface wave.

This is not just by the flinging fields so at millimetre wave frequency typically we face these problems the detrimental effect of TM 0 mode particularly for micro strip line.

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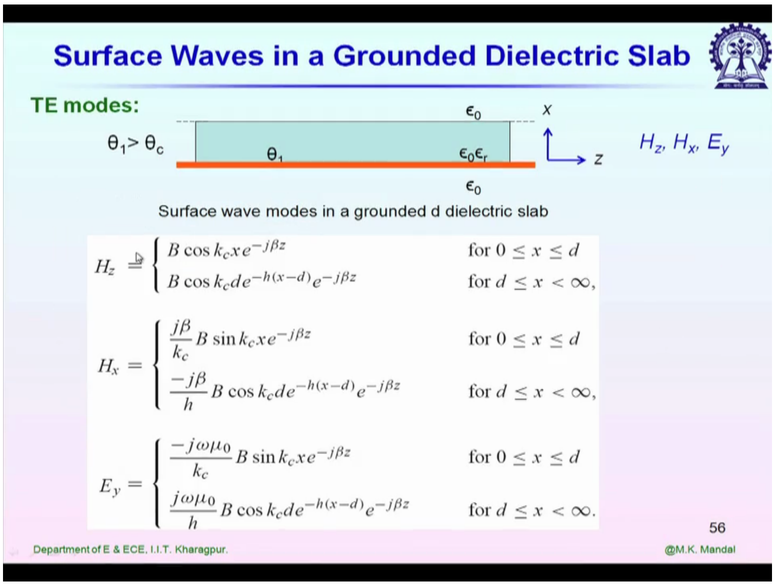

Now the next mode is TE mode in this case the dominant electric and magnetic field component are EY, HZ and HX so what is the direction of EY? EY its perpendicular to propagation direction and the ground plane its in ZY plane now so EY is also parallel to the ground plane.

So on ground we don't expect any EY component since its a conductor now look at the expression inside dielectric we have sinusoidal variation so at X equal to 0 , EY is 0 and then it increases at as we increase the HX and it has maximum value at the interface and inside air it decreases exponentially .

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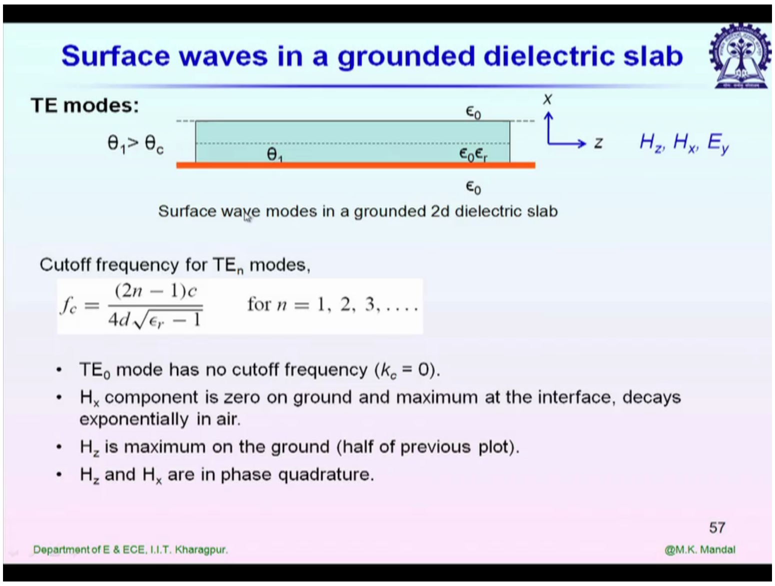

TE 0 mode it does not have any cut off frequency for other modes the expression is little different than TM mode cut off frequency. We can calculate FC as twice N minus 1 into C divided by 4D square root of epsilon R minus 1.

So C is the velocity of light in free space and D this is the thickness of dielectric slab and epsilon R this is the dielectric constant of this slab. Now usually for a micro strip line we don't face any problem for TE mode. But we face problem for the CPW lines. Why? Let us first see the field plot of a CPW line.

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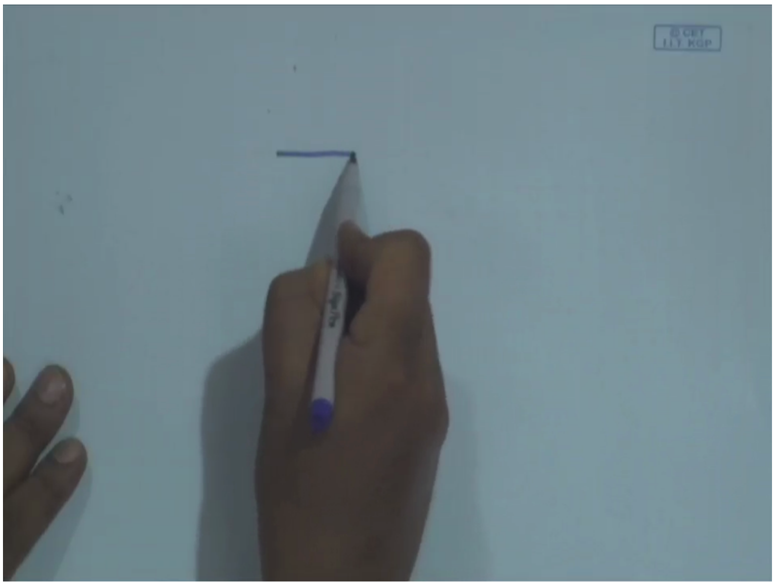

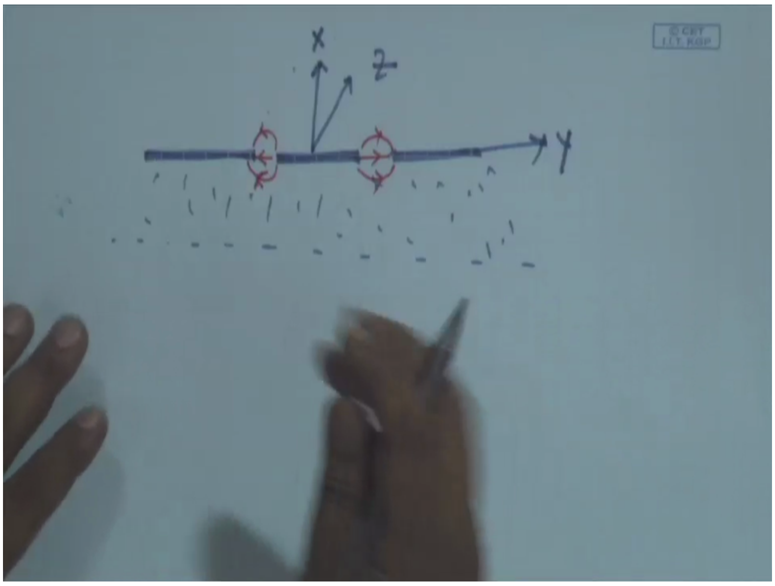

So how the CPW line it looks let us say this is the central strip of a CPW line and we have left and right ground plane. So I am drawing the cross section and it is seating over a dielectric. Now if I plot the field so its starts from signal line and terminates on the ground left and right ground now what is the wave propagation direction we consider? Wave propagation direction is Z.

And the perpendicular direction we consider X and this side this is the Y component and If I go back to the solution you see in this solution we have EY components so EY it is maximum at the interface and then on ground plane obviously its small.

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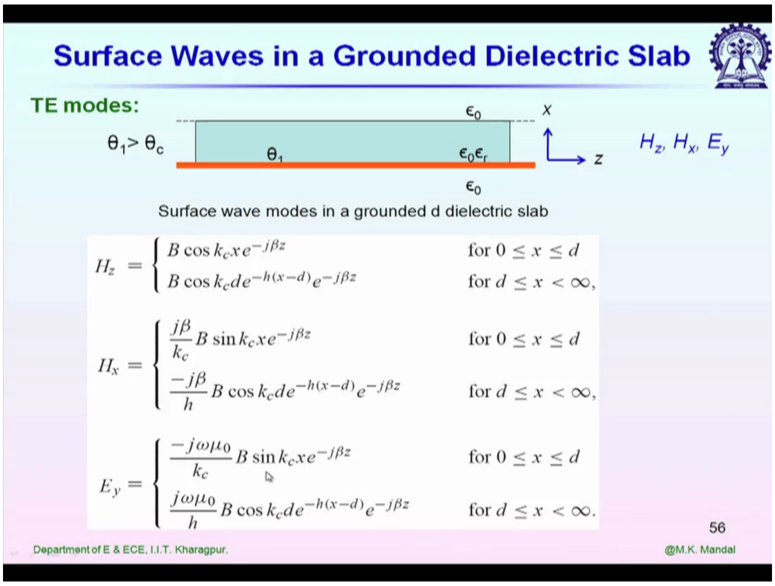

But since we have EY component for TE 0 mode which has no cut off frequency then TE 0 mode it is easily excited by the CPW line. And we have similar problem as we have seen for the micro strip line. So somehow then we have to avoid this TE 0 mode or the effect of TM 0 mode.

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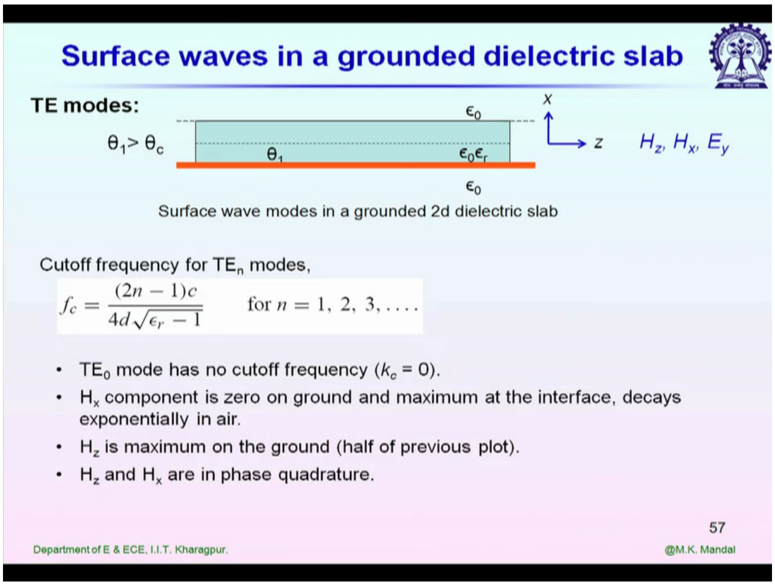

In practice there is no way to completely avoid the effect of this TE0 or TM 0 mode but still we have some solution by which we can reduce the coupling to some extend.

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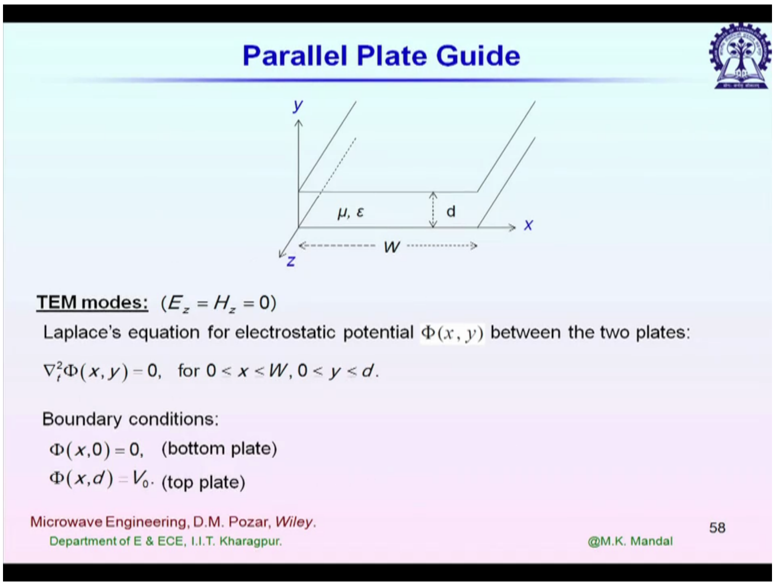

So for example if I consider the effect of TM 0 mode and how to reduce it So let us go back to the diagram.

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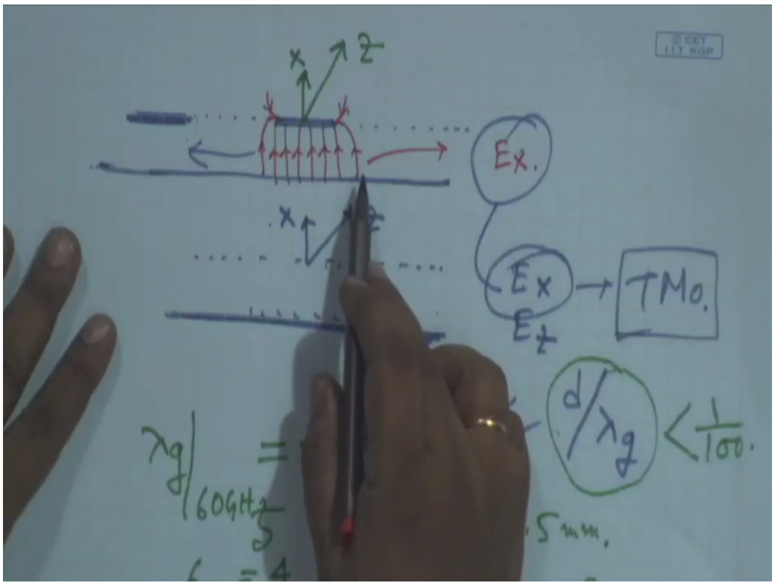

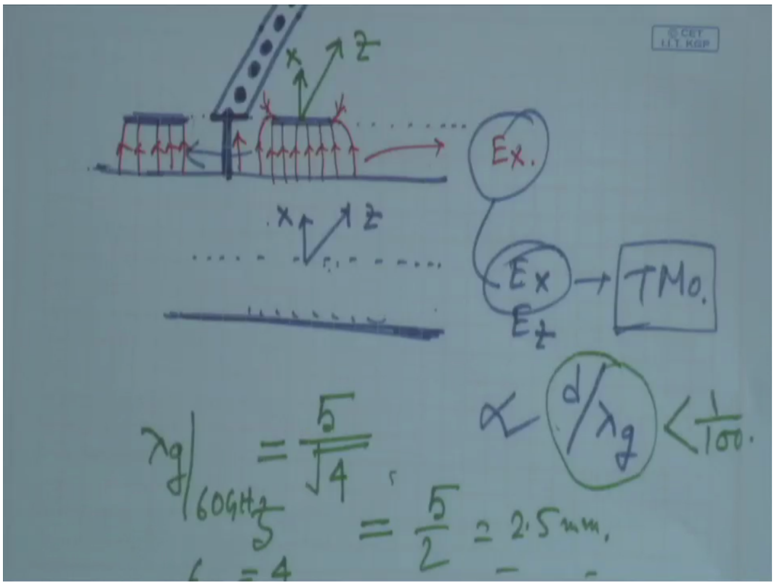

So for TE 0 mode sorry for TM 0 mode what we see the main problem is coming due to this X component of electric field which is perpendicular to ground plane. Sorry now I want to avoid coupling between this 2 side by side line and so what we have to do? We have to do some modification which does not couple power to the surface wave mode.

So what we do practically? We will be using 1 more strip between this 2 micro strip line and then use a metal via which connects these stop strip to ground now since the electric field EX component is parallel to this via it will be suppress by the via. So the only thing what we have to? We have to use periodic via to suppress this EX component.

So in Z direction this via will be periodic and the separation typically we use less than lambda g by 4 at the highest frequency of operation. It can suppress this coupling to some extend let us say by 10 to 15 Db. But it cant avoid the effect completely. Okay so let us take one break then will see the other parts.