Hello and welcome to NPTEL mooc on electromagnetic waves in guided and wireless media. In this mode we are going to look at how can we construct structures, which can guide electromagnetic waves from one point to another point. Now we have already seen such structures, okay. The first structure is the one that has no structure at all, meaning that it was the free space. So in the free space, you know, if somehow we were able to generate the electric and magnetic fields, whose electric field say is along X direction and whose magnetic field is along the Y direction, then this would be the electric and magnetic field picture that you would see, these are the electric field lines and these are the magnetic field lines and these lines are kind of cross or perpendicular to each other and this pattern essentially propagates through the free space or a medium, which is homogenous, filled with dielectric or some permittivity epsilon are and the corresponding expression in terms of the propagation was given by something like E Par J omega T, where omega is the frequency of the sinusoidal wave times beta Z, okay. and the amplitude was essentially constant. So if for example we are writing the electric field, the electric field was the function only of the propagation direction Z and time as well and it actually had a constant E0 and this constant vector if it is directed along the X axis that we have chosen, then this we would have called as the X polarized plane wave, if it was Y, we would have called it as a Y polarized plane wave and then the corresponding expression for H also, we have written, right. And what is that we have observed is that these waves are also going from point A to point B, they do carry a pointing vector S, which is given by E cross H in the instantaneous case or half real part of E cross H conjugate, when you convert all the quantities in terms of the phases, right. So in some sense the pattern that we have seen, the X and Y, you know, lines that you see here, this cross pattern that you see can be thought of as the mode, and this mode which satisfies Maxwell's equation as well as the boundary conditions, well in this case there are no boundaries, so the only condition that you are satisfying is the Maxwell's equation. And any such pattern, which would satisfy Maxwell's equation and if there are boundary conditions, can be called as a mode. Therefore please take this as a take away of this you know, whatever, that we have been discussing over the last few modules is that plane waves can be considered as modes of the free space media or a homogenous media., okay. So that was free space. Unfortunately the problem with free space is that the wave, you know, amplitude, first of all they are not, you know, mathematically, well mathematically they are possible, but physically they are not possible, because that would require the energy to be very high. It would actually be infinity, because you can imagine a cross section, which could extend all the way from minus infinity to plus infinity, you know a square in the X Y plane, and then you would see that electric field and magnetic field in the corresponding S will be a constant in that entire space and the overall power that you are going to get or energy that you are going to get when you integrate the pointing vector would be non, I mean it would actually go to infinity, because you can extend the area. So moreover these free space, the uniform plane waves that we have taken do not have a focusing kind of a property. Like you know, if for example my, how do I receive such uniform plane waves. I mean, I can put up my receiver in some way, we are going to talk about what kind of receivers we need to use, but there is not… there is no focus. I mean, this receiver is no more special then a receiver that would be put at another position, right. So because of this they are not really being guided, more so they are kind of flowing. So yes, free space is also guiding waves, but in this sense, the word guide is not very tightly defined for the free space waves. We then found out a different kind of a structure, in that in at least in the integrated optical circuits, what we found was that if you take a slab of some permittivity as M1 and refractive index N1 and then surround this slab of materials which have permittivity or here refractive index N2 less than N1 and in this case N3 also less than N1, then it is possible for us to have guided waves, which would propagate. And if you assume for a minute that you are looking at the electric field component of this one without bothering whether we are dealing with the TE or TM modes, then this electric field actually had some function of X, correct, because I am assuming that this direction is along X direction and this direction is along Z directions. The waves should propagate along Z. So in terms of the phaser we had this E Par –J beta Z and this function F of X ray, right. And different type of functions were present. So one example for the symmetric case that we saw was that, in between you had, that is in the slab you had a nice cosin wave, sorry or a cosin wave, right. This is the center of the slab that I have taken that is this particular line and then outside you had actually this exponentially tapering off or exponentially decaying fields, right. You could of course have a sin kind of a variation as well. She this was another mode that would also decay out and you could have more such kind of decaying and that such kind of variations within the slab. So these are all correspondent to different sin and cosin functions, oscillating with respect to whatever the KX oscillation corresponding to the KX value of these fields. But it was important to… it is important to distinguish that these are not plane waves, which is very obvious, right. You look at these two expressions. Although we have not specified the form of F of X, I told you that these are trigonometric cosin and sin functions. Such a function is absent in this E0, right. So which clearly indicates that although in terms of the phaser, the propagation part along Z is the same for both types of modes, this particular mode is more confined in the slab and the outside, you know, of this particular slab, the energy basically decays rapidly, even exponential form. And this is you know, kind of matches, this kind of matches without expectation of how a mode or a wave would be guided inside a material, right. So you can imagine that I actually have this kind of a slab, okay. So this is the slab that I have and then this is the Z axis. So the mode which would essentially look something like this and exponentially decaying, would actually propagate along this particular direction. So the mode is actually propagating from one point to another point. It would be propagating along this Z direction, okay. So this was one type of a structure. We also saw another structure, although we did not discuss into great detail because the equations were going to be very complicated, but we also saw that this structure, which is called as optical fiber, works basically on the same principle that you have N1 les than… I mean N1 in the core and then N2 in the cladding being less than frequent… I mean less than the refractive index of the core. And then again the solutions were slightly different. They were not really F of X, but they were kind of Bessel functions of appropriate order, right. So some J Nu of R, where R is the radial distance along the center, right. So in the fundamental case, which we said in the weak guiding approximation, you are going to get something called as linearly polarized modes. In this case you had LP01 or LP11, these are the different orders of the modes and the mode structure was getting more and more complicated, right. In fact the basic difference between this integrated optical structure that we saw and this one is not only that you have the mode function, which is different from the previous mode functions like F of X becoming J Nu of R. The point with this electric, sorry with this optical fiber is that you not only have the X component, or in general you have all three components, ER, E Phi, and EZ. In the weak guiding approximation, you can have only ER and E Phi, but there will be a very weak EZ or weak HZ, depending on which mode that you are looking at. So in general the two solutions of an optical fiber will have all six non 0 components ER, E Phi, HR, H Phi, EZ, and HZ, but in the weakly guided approximation you can say that EZ and HZ are kind of very weak, compared to the transverse components ER and E Phi, E… HR and H Phi and because R and Phi plane can be equally talked about in terms of X and Y, can be converted into X and Y plane. We normally talk about EX, and EY, and EZ. EZ is in terms of magnitude very small, compared to EX and EY, okay. But the point is these two had a certain mode structure. These modes are essentially those electromagnetic solutions or solutions of the electromagnetic equations, would satisfy Maxwell's equations and in addition they would also satisfy the boundary condition. In this case you have a boundary at R=A core and another boundary, which we are taking it to be quite far away from the core itself. So what I am trying to get to you is that, when we say a mode, there is only two conditions that a mode has to satisfy, one is Maxwell's equation, okay. These have to be satisfied by all modes, obviously, otherwise, if you have electric and magnetic fields, which are not satisfying Maxwell's equations, then they are not true solutions of electromagnetic field model. So clearly that cannot happen at least to our situation that we have considered. And then we have to satisfy the boundary condition. These waves have to satisfy appropriate boundary conditions and depending on the type of a geometry, the boundary conditions will also slightly be, the… will result in components, which are different from one component. So for example, in the plane R slab case, the mode condition was sinusoidal or the boundary conditions were on a plane and therefore the solutions that you get F of X, were all trigonometric functions, but when it comes to optical fiber, the structure is cylindrical, so the corresponding variables have to be used.

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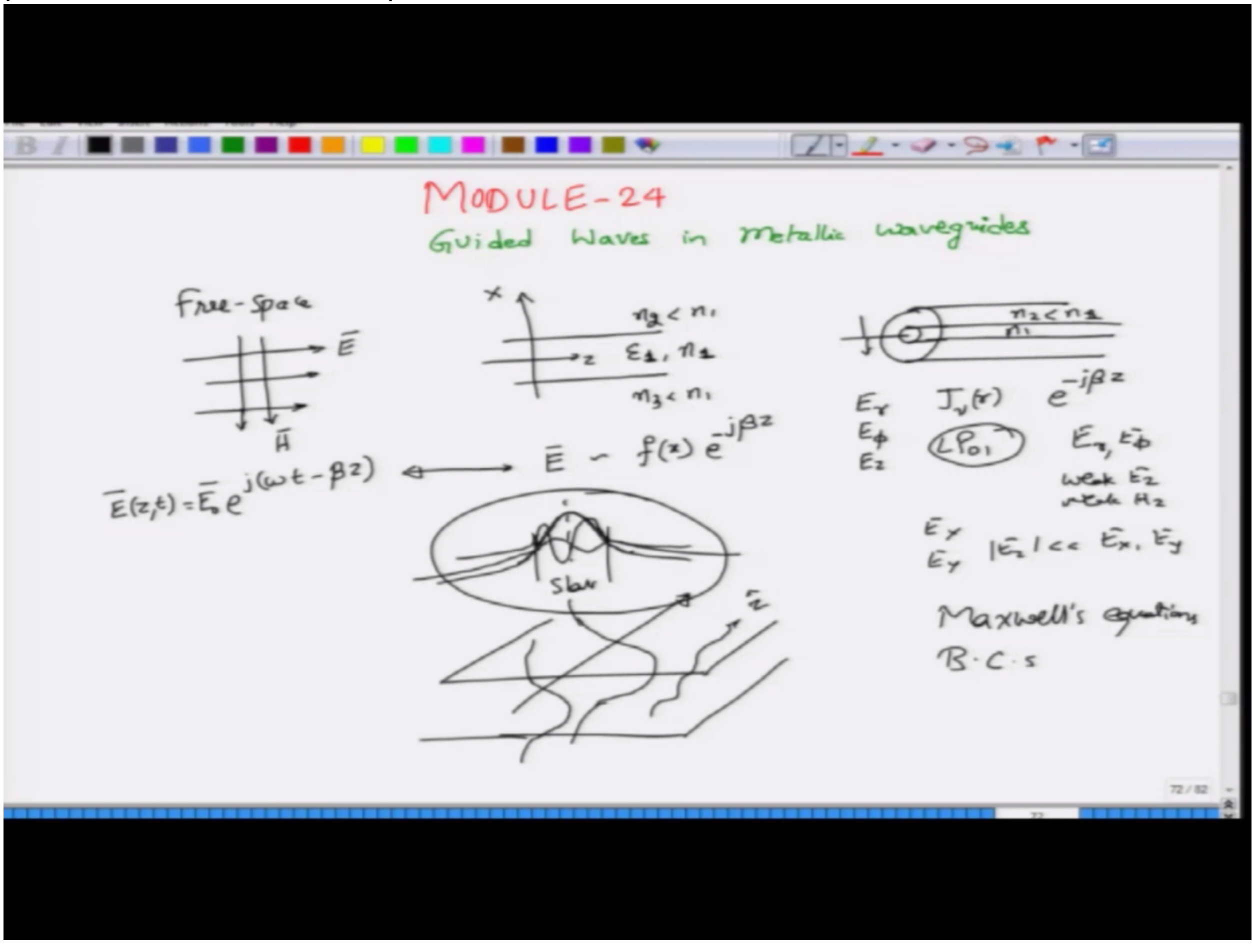

In between this, we have also seen one more structure, in fact we started the course with this structure, okay, and that structure happens to be the transmission line, right. We have not really looked at the electromagnetic analysis of this transmission line, but suffice to say that transmission lines are essentially carrying this free space, the uniform plane wave types, okay. If you instead of working with the voltage and the current, you work with the electric field and the magnetic field, you will see that the wave structure that will be present on this transmission line will have the same, you know, characteristic in some sense. So your electric field lines will be directed from top to bottom and the magnetic field lines will be curling around the top structure, so it would be curling around in this around, it would be curling here, and it would be curling in the opposite direction and you can actually show that you can have a one to one relationship between free space and the transmission line structures. In fact we will look at the electromagnetic analysis of transmission as a special lecture in some other, at the end of the module, where we will also look at the equivalence of describing transmission lines in terms of voltages and currents or in terms of electric and magnetic fields. So these are all the different structures that we have seen. Although the first one is really not a structure, but what is interesting about these structures is that they do guide waves, okay. Whether they will be completely confined or partially confined, they are all different things, the important point here is that they are not operating at the same frequency, okay. They can be made to operate at the same frequency, but the dimensions required will be very-very impractical. For example, you can have a dielectric wave guide, which would be operating in say 1 K Hz, okay. In that case the core width that you have to, you know, have will be in a few km, right. You know, you have to construct an entire slab of a few hundreds of meters to a kilometer so that the electromagnetic waves at 1 K Hz can propagate, okay. The reason for that will become clear, when we talk of detraction in some other module after a few modules here, but that is essentially the point, the higher the frequency, it's kind of easier to squeeze the modes in, and that is why these integrated optical frequencies work very well at tera Hz, where the core widths can be just about 2 to 3 micrometers and surrounded by of course the cladding of appropriate width, whereas this optical fibers will operate also at tera Hz or 10s of tera Hz, whereas their core diameters will be somewhere around 8 to 50 micron, okay. So 8 for the single mode fiber and 50 for the multimode fibers. So these structures on the other hand, the transmission line structures are good, maybe up to about say 2 GHz or maybe up to say 10 GHz, but again transmission lines are not just a pair of wires, because a pair of wires are good at low frequencies, but as you get to higher frequencies, you for example have to look at this micro strip line as we have already talked about, right. So you do have different structures, which are tailored for different frequencies, simply because some structures are useful in squeezing the modes at those frequencies, whereas if you try to make the same structure for other frequencies, then the required geometrical parameters will be so huge that it would be impossible or impractical to build such.

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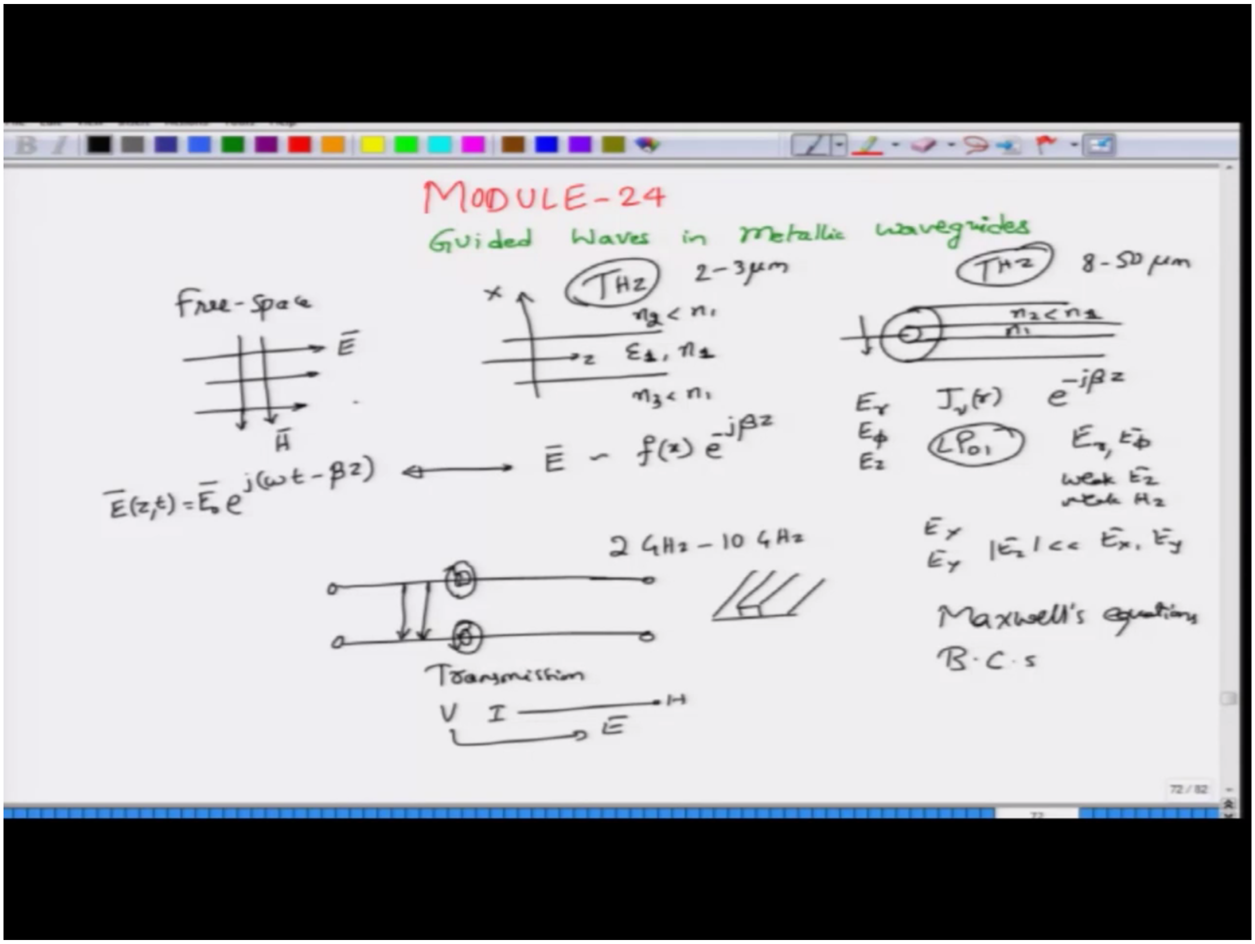

Okay, so this is all guided waves that we have looked at. Now we are going to introduce a different wave guide, okay. In fact this wave guide is very similar to, you know, transmission line structure that we have looked at. So in some sense we are doing a transmission line analysis, but then this is not a line, but this is a plane, okay. The basic idea here is that, I am going to introduce the basic idea, so we are going to look at… so let me, before I go to that one, let me also tell you that the confinement mechanism in this integrated optical wave guides as well as the optical fibers was what we called as total internal reflection, okay. Whereas the confinement or the guided waves in this transmission line structures, the waves themselves are called as TEM waves and sometimes these lines are called as TEM lines, whereas the confinement actually or the guiding actually comes from the two wires that we have actually taken, okay. These wires are of course made out of metals, so there is really no total internal reflection happening, it's a pure reflection phenomenon that is happening, which we will look at it in this slide or in this module now.

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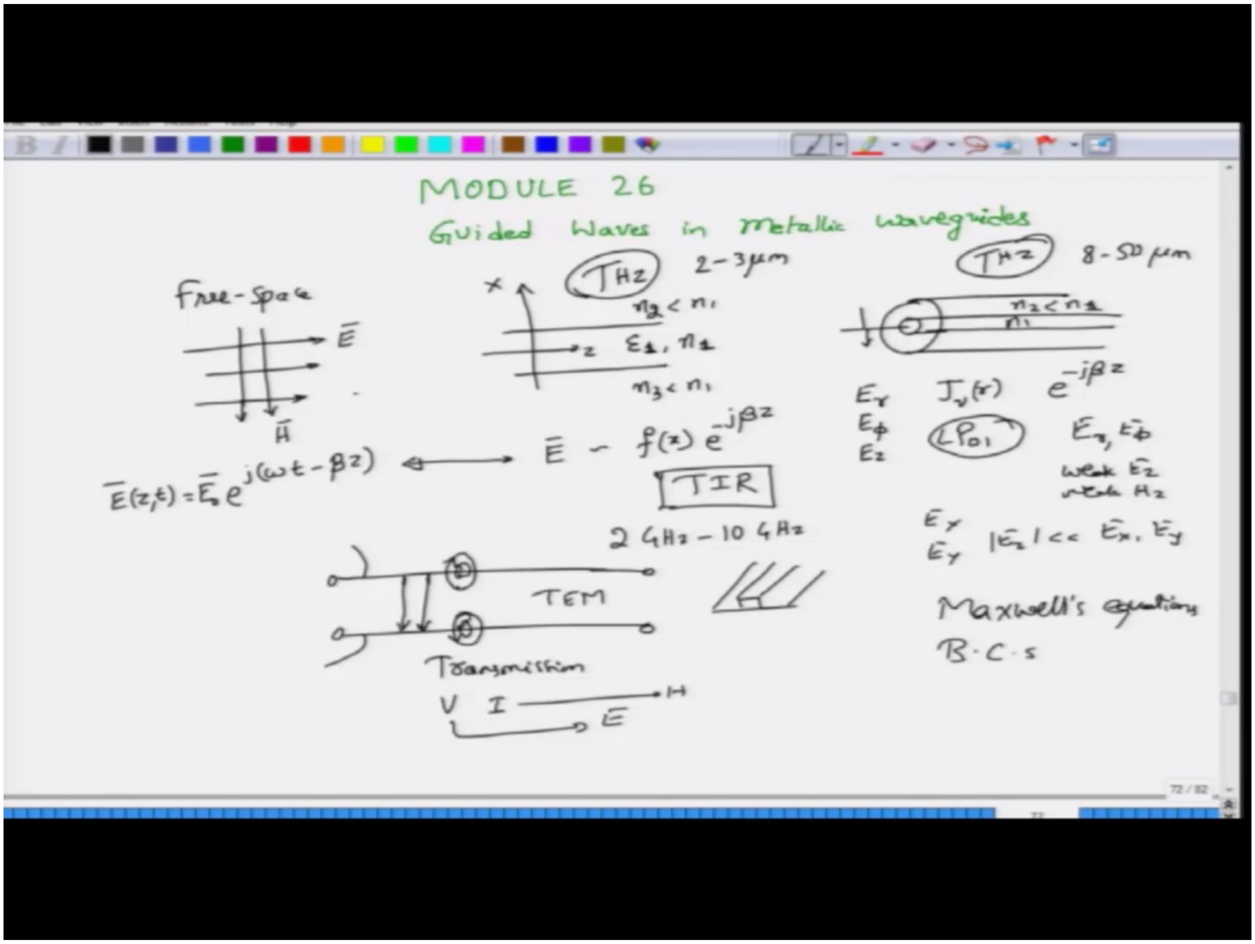

Imagine that you have two planes, okay. These planes actually are you know, assumed to be wide in the X and Y directions, let me get the coordinate system right. So I am going to assume that this direction is along the Z direction, this direction is the X direction and we will assume this one to be at X=+A and X=-A. So I am actually putting two planes here, so you just imagine that these two are two planes and then the horizontal distance that is along this way be will be the Z direction and if you look form the top, it would look like a big square and the square we will assume it to extend all the way from X from minus infinity to plus infinity and Y from minus infinity to plus infinity, okay. However, because you have considered two such planes, there is a discontinuity in the X direction. So that is as you go, you will not see a plate, then you will see a plate, then you go north, no plate, then you will see a plate, and then again you will go and see a plate. However, on the Y axis if you move, you will only be seeing the plane, plane, plane, you know, like you will be seeing only the plate-plate-plate essentially. So these structures are called as parallel plate wave guides for very obvious reasons that there are two plates and these plates are actually kept in parallel with each other. The distance between these two plates, I have taken it to be 2A. It is conventional to take the distance as D, but I just wanted to

put a symmetry around these two plates, so I just took them as X=A and X=-A, okay.
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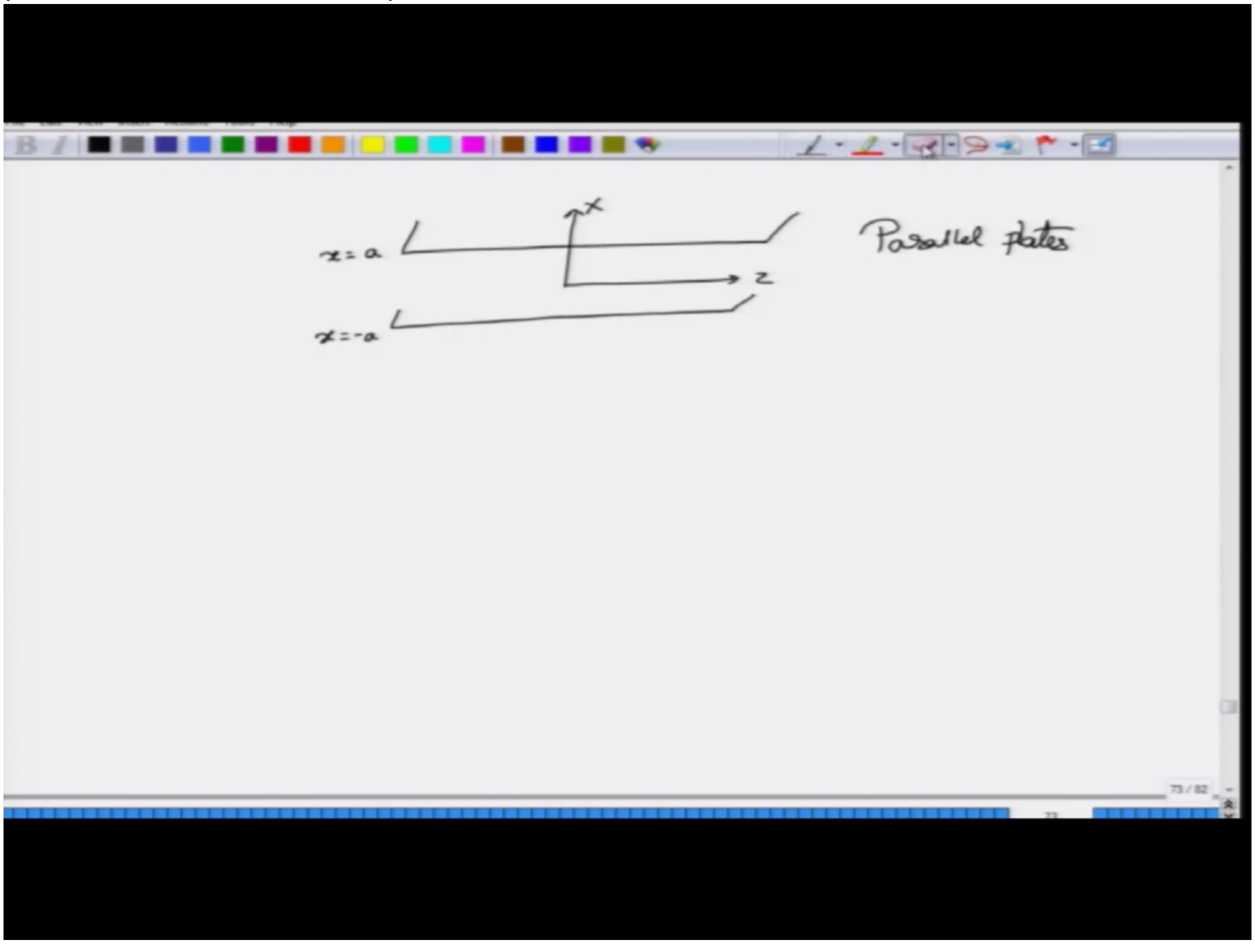

Now… now I won't analyze, to analyze the mode function or modes of this particular wave guide, I will assume that the lower, this one can be neglected, right. That is the lower plate, I am removing this, okay. And instead I will imagine that light has been incident, okay. I will, you know, incident at an angle of say theta 1 and this is the electric field component say E1, which I have written, or sorry, this is the direction of propagation, which we will write it as K1, okay. So this is K1 and there will be an electric field component associated with this, okay. These plates are essentially perfect electric conductors, which means their sigma goes off infinity, okay. And you have this K1 as the direction. Now you have to obviously ask me or ask you know, pause the video and then think about a little bit, what way should I put the electric field in, because I know that obliquely incident waves, electromagnetic waves can be either TE polarized or TM polarized with respect to the plane that we considering. So I will have to pick something out. I am going to assume that the electric field is actually along the Y direction, okay. So making transverse electric to be the case that I am considering. This has been done just to simplify some of the steps, however, I would encourage, and strongly urge you to actually carry out a similar analysis using TM equations as well, okay. But for now we will look at only TE case and get the basic ideas behind what kind of mode functions, I am going to get, okay. Now this light has been incident… oh sorry, this electromagnetic wave has been incident at an angle theta 1 with K1, what would be K1? K1 in this case is obviously given by K1 cos theta along X direction + K1 sin theta or theta 1 here along the Z direction, right. So this is the K1 vector that we have. Now you have a perfect electric conduction. What should happen to this wave as it strikes a perfect electric conductor, it's a metal, right. So metals won't absorb light and this is a perfectly electric conductor, so what it actually does is to you know, reflect of this, not light, reflect of this electromagnetic wave at the same angle theta 1, okay. So the electromagnetic wave is now reflected off and then reflected wave will also be… transfers electric polarized only, so we can call this as EYR and this amplitude as EYI, okay, and then this is reflected back. Of course there will be a magnetic field associated with this one, which you can easily find out, but I am not interested in finding the magnetic field, I am interested in the electric field itself, okay. Far away from the interface the total electric field in region 1, which I am calling this as the region 1 will actually be equal to the incident electric field and the you know, reflected electric field, correct. So EY… EYI and EYR, what would be the incident electric field, which is basically some amplitude, which we will call as some E0 or let's say we will call this as E0I and then you have E Par –J K1.R + E0 R E Par –J K2.R, right all of this is actually along the Y direction, therefore I can take the Y as a common factor out, okay. Now what is K2? You can see that the direction of K2 is such a way that it is moving away from the X direction, right and when you decompose this K2 in terms of its X and Y components, you will see that along Z it would still remain the same, so it would be still K1 sin theta 1 Z. Can you tell me why K1=K2? Think about it, okay. However, on the X1 it would be –K1 cos theta 1 X Hat, okay. Your R vector of course is given by X X Hat plus Y Y Hat, sorry, Z Z Hat, which basically describes any point in this plane, okay so this is your position vector R. Now what is the boundary condition that we have on a perfect electric conductor, the tangential component must be equal to 0, right. So the total tangential component on the boundary must be equal to 0, which means that at X ray=0 and we also know that for the phase factors, Z at any point of Z we should have the same condition, that of course will give you the Snails law and other things. What this essentially implies is that the reflected EOR amplitude should be = -EOI, okay. Because we said this one equal to 0 and ask this equation to be equal to 0 for all values of X and for all values of Z, we will essentially get that EOR = -EOY. With that the total electric field in region one, I can rewrite it as EOI is a common, I'll pull this out, and then you have E Par –J K, so let me call this K1 cost theta as KX and K1 sin theta as KZ, okay these are two auxiliary variables that I have introduced, which are related to the original K vector as well as the angle of incidence theta 1, okay. So we can write this as e Par JKX X, E Par – JKZ Z – EOI, right, E to the power +JKX X, please note that along X now K is –X kind

of a thing and then for Z, it will be E Par – JKZ Z, okay. And instead of writing KZ, we will go back to our original notation for propagation constant along Z and we will call this as beta, okay. So you have EOI, which is the amplitude – E Par – JKX X – E par + JKX X * E Par –J beta Z, which would essentially be present all the time. So this is clearly showing you that there is some function of X that is getting multiplied with E Par –J beta Z, which will describe the total electric field in the region away from that plate and that looks… starts to look very similarly to what we had done for the slab wave guides, except that there are no waves outside this perfect electric conductor, because the… there is no evanescent wave, at least not what we are considering, we are assuming perfect electric conductor, so there are no evanescent waves outside, or we will assume that the evanescent waves, even if they are present, they have died on so rapidly that you don't even have to go beyond a few nanometers or few angstroms above this perfect electric conductor region, that you will actually see anything of that decaying sort of a thing. So it's a perfect electric conductor, light is instant at an angle, it gets reflected, instead of light I am talking about electromagnetic wave, which are essentially same, gets reflected, and when you move away from the interface, at some point when you look at the total electric field, the total electric field will be something like F of X, but it would be propagating, right, along the Z direction, right.
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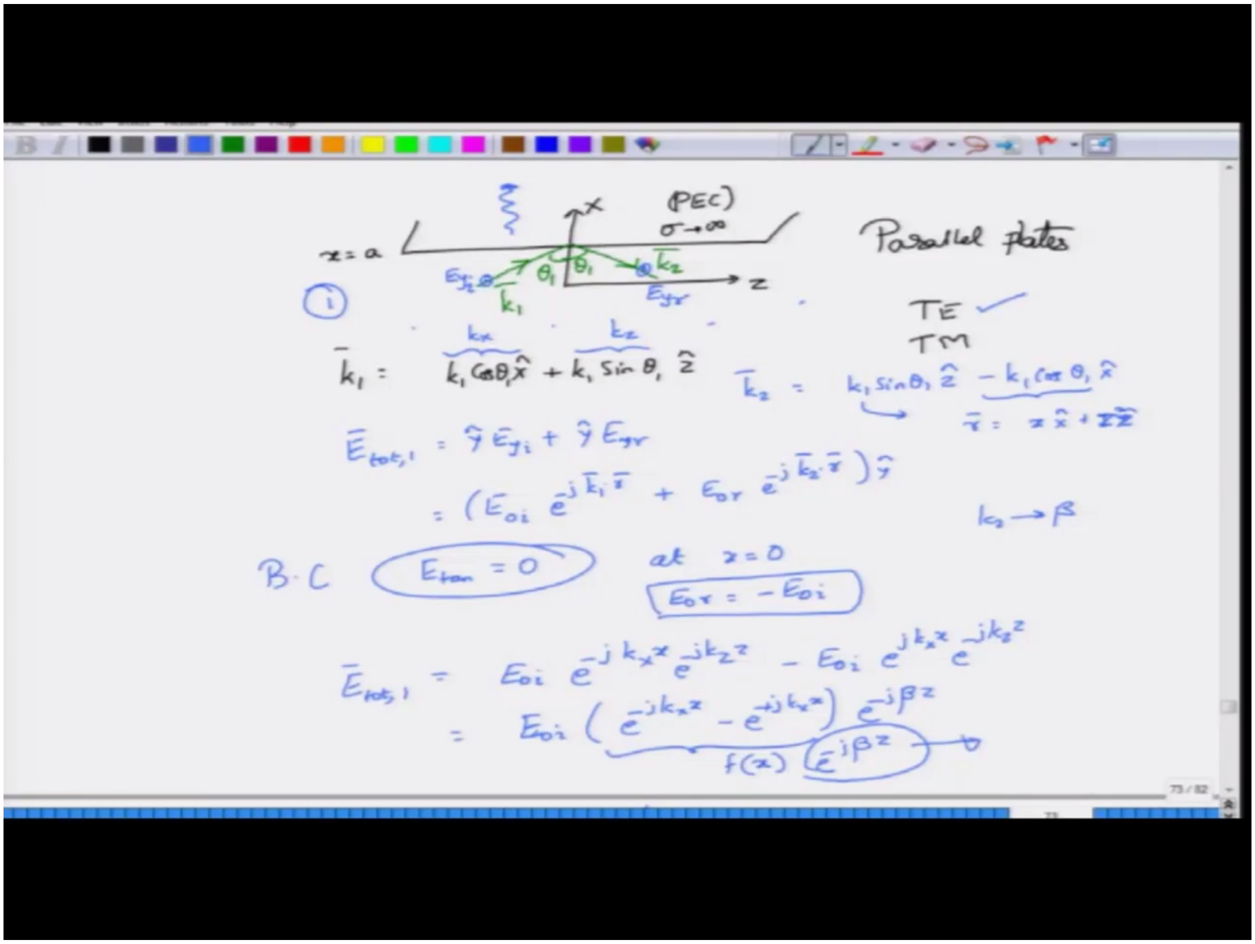

What is this F of X, let us look at it. See you have E Par –JKX X – E Par + JKX X. So if you use the trigonometric identities, you are going to get this as -2 J EOI sin KX X, right and then you have E Par –J beta Z. So this is the total electric field in region one and if you now plot this total electric field in region one, okay, the magnitude of this one, what you will actually see is that here we had this plate, correct? And this plate was kept at X=A and obviously at X=0, sorry we kept this one at X=A, right sorry, hold on. We will keep this plate at X=0 initially, sorry… sorry about saying that. So I will keep the plate at X=0, the rest of the equations won't change, I mean there is nothing that has changed at this point, but we will just take this X=0 to begin with. So yeah, in that sense, I am not really creating a symmetry, but the equations won't change, nothing has changed so far, only… even the boundary conditions hasn't change, right. In fact we used X=0 as a boundary condition, but I forgot to tell you that, okay. So nothing has changed. You simply have the plate coordinate moved at X=0 and now when you plot the magnitude of this electric field, what you would find is very interesting. At some Z, you have to take of course, because it keeps changing along the Z, but at some Z, this term will be equal to 1, the magnitude if you take and what you get is the magnitude of sin KX X. Now let's catch that at X=0, sin will be 0 and then it will reach a maximum at some point and then it will again reach a maxima and then it would actually go back in this particular manner. You can clearly see that this is beginning to look like a reflection from a short circuited transmission line, if you think of the transmission line as still. Of course, you don’t have to think in that way if it is just a plate that has been kept, then you simply have the waves, which are moving in this direction. And at the points where you see the total electric field going to 0, it's because of the destructive interference between the forward going wave EOI E Par –J K1.R and the reflected wave, which is EOR E Par –J K2.R, right. Of course K2 magnitude = K1 magnitude in this particular case. Now let's do a clever thing. I have this plate already, what if I go and insert another plate at this point, where the field is actually going to 0. Where does the field go to 0, well it is a sin point, where it is going to 0, right. So where does sin KX of X go to 0? It will go to 0 at all those planes, which would actually satisfy this condition, that is at all planes of X, such that KX times X=N Pi, where N is a number, it's an integer for us, then this field will go to 0. So the first time that it goes to 0 at this point is X=0 and where does it go to 0 again? It would go to 0 again at say X equals, let's take N=1, because if I take N=0, I don't have any solution here. So with N=1 as the first solution that is possible, next point where it goes to 0 is when X=Pi by KX, but what is Pi? What is KX? KX is basically Pi divided by K1 cos theta, right, which actually means, we call this entire thing Pi/K1 cos theta, and sorry, it is cos theta 1 as A, okay. So I will call this one as X=A, where A is of course given by this particular expression, okay. So whatever, that X value, which satisfies this equation for a given value of theta 1 and for a given value of K1, we will call it as N, and we have put in a second plate at X=A or maybe we can put the plate at X=-A because you know, I took this as a positive X direction, but it's really immaterial, whether you put it a +A or –A, you just have to change N from being positive one to minus one, it doesn’t really matter at all, okay. The condition that is necessary is that KX times X should essentially give rise to N Pi total face shift, where N could be any integer, but the first such instant that we would have would be when N=1 and this is the equation that you get, okay. Let's simplify this equation slightly in terms of theta 1. Suppose in practice what happens is, I will be given some X=0 and X=A and then asked to find those values of theta where the electric field can actually go to 0, right. So I will rearrange the equation to make it cos theta 1 = Pi/K1 times A and K1 being the wave vector, I can rewrite this as 2Pi by Lambda times A and then I can cancel Lambda… Pi from both sides and then you have Lambda/2A, right. So all… so the first time when you are going to get the angle of incidence theta 1 for a fixed value of Lambda and for a fixed value of A is that. So if you send in light at that particular instant, the light that gets reflected causes the overall electric field in region, right, below the first plate to actually have this periodically going to 0 and this particular insertion of a second plate at X=A, does not really change anything in terms of the field. The field is automatically satisfying the boundary conditions here. So the field is automatically satisfying boundary condition and therefore this structure can actually be considered as a wave guide. Of course you can put more such plates, but then things can, you know, you don't want to put more plate, because there is no reason to put more plates, right. And the moment you put plates, there won't be any waves in this region as well, because this is also assumed to be a conductor.

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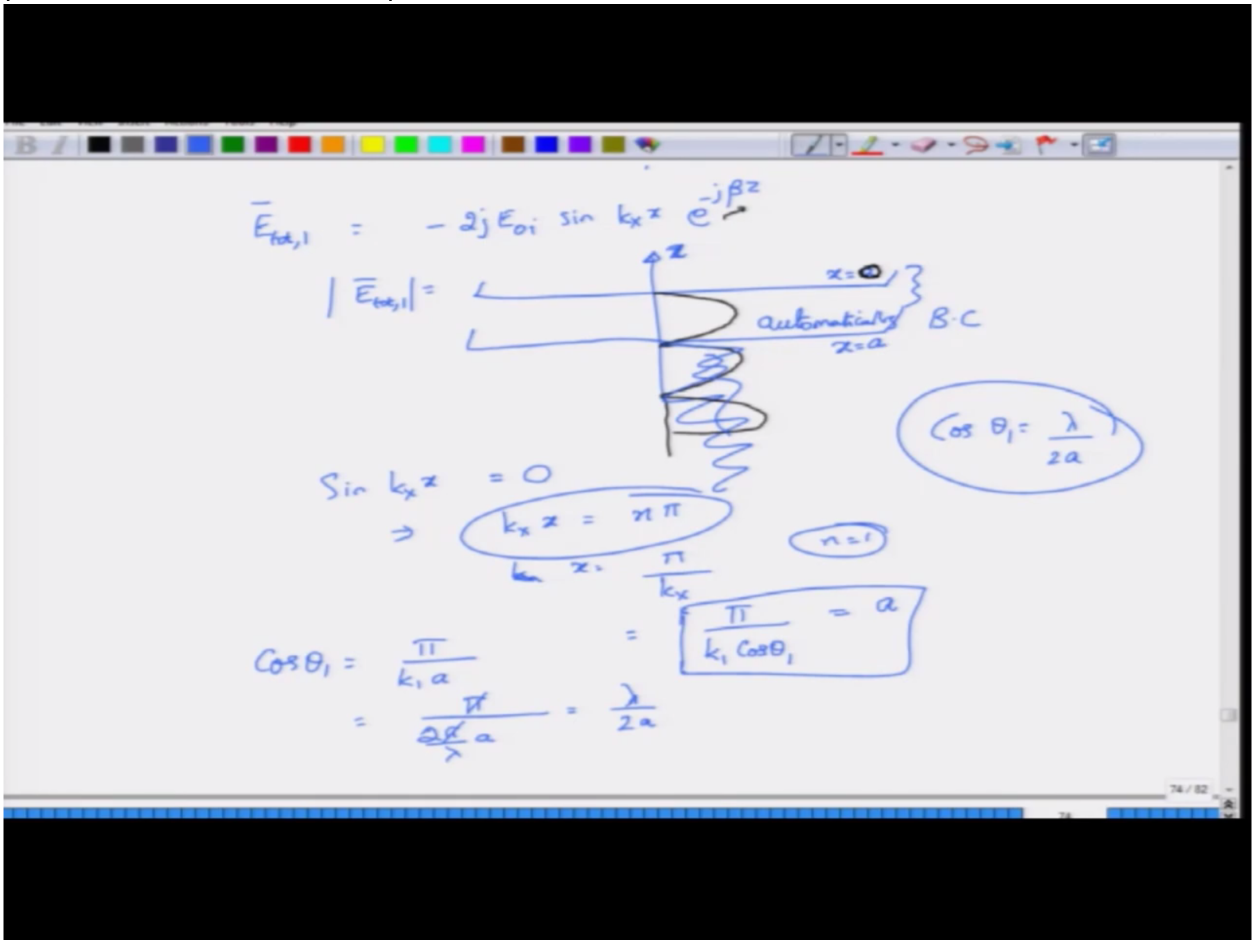

So you have automatically satisfied Maxwell's equations by putting two plates at X=0 and X=A and the wave can now begin to move in the Z direction just as it would have done in the case of a dielectric planar slab waveguide, with the additional advantage that there are no evanescent fields at least when your conductivity is very-very high, there are no evanescent fields outside this particular slab, okay. This is the, and again in a same way that you have a dielectric wave guide, you will have TE modes, TM modes. The value of N will tell you how many such half cycles you are going to have inside the slab so that can be N=1, N=2, N=3, and so on. Of course N=0 is no point. So you can, you know skip that particular value of N in this one and then you have this cos F of X. So the point here is that you can think of waves propagating inside this metallic or parallel plate waveguide in terms of obliquely incident and reflected waves, meeting with respect to each other. So a picture that is very similar to dielectric slab waveguides, but this is… this picture would work in the range of say about 3 to some 100 GHz, not really in the tera Hz regions, and these are called as parallel plate wave guide. They are extensively used in, a variation of these are used in microwave wave guides. Thank you.