

Transmission Lines & E. M. Waves
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Lecture No. # 40

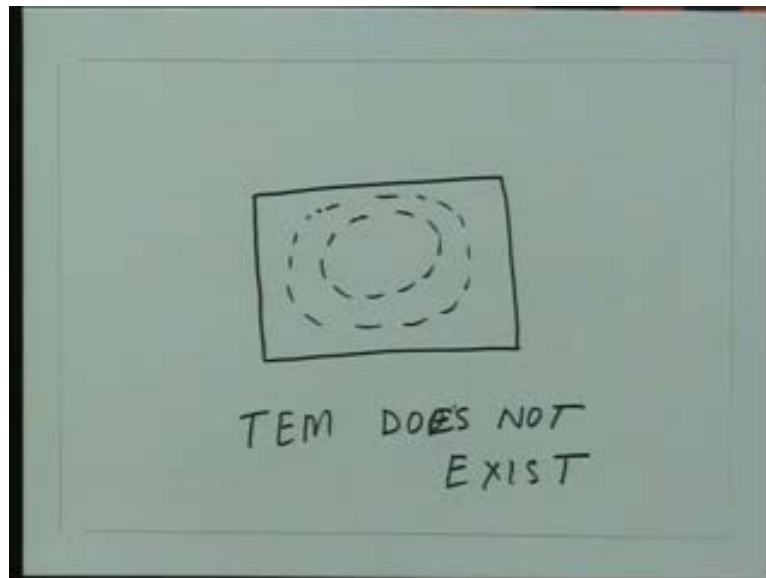
In last few lectures we investigated propagation of an electromagnetic wave inside wave guiding structures. First, we investigated propagation inside what is called a parallel plane wave guide and later we derived the fields inside a rectangular wave guide. Of course the approach which we took in two cases was different. In first case that is for parallel plane wave guide, we visualize the propagation of electromagnetic wave as the propagation of uniform plane wave by multiple reflections at the two conducting boundaries of the parallel plane wave guide whereas in case of rectangle wave guide we took the mathematical approach that is we simply said if you wanted to have a transverse electric or transverse magnetic field, mathematically just solving the wave equation in satisfying boundary conditions what kind of fields we would get. The visualized wave which we had in case of parallel plane wave guide they were the physical understanding of what kind of field can exist inside a wave guiding structure and from there only we understood that if we go perpendicular to the planes, the conducting boundaries then we will have the wave which will be standing wave kind of waves whereas along the plains you will have traveling wave and using this physical understanding we can appropriately write the mathematical functions for electric and magnetic field inside a rectangular wave guide.

So, in one case we had physical visualization of the phenomena in other case it was a purely mathematical approach and now we must verify that mathematically which we did blindly for the rectangular wave guide, does it give me the fields which we have derived from the physical understanding for the parallel plane wave guide. So, essentially what we have to do is we have to establish that the fields which we got for rectangular wave guide, if we take the limiting case then the fields must represent the fields which we got for the parallel plane wave guide.

So, now what we will do is we will do an exercise of showing that these fields which we got for the rectangular wave guides indeed represent the fields which we got for the parallel plane wave guide is the limiting case when one of the dimension of the wave guide becomes

infinity and then we are also ask a question what happen to the mode which was TM 0 mode which became the TEM mode in the parallel plane wave guide. What happen to that mode in the rectangular wave guide? Does it mode now exist inside rectangular wave guide or it exists only inside the parallel plane wave guide?

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So, let us take first the second question that is does the transverse electromagnetic mode exists inside a rectangular wave guide. This we can argue physically that if we consider a rectangular wave guide and let us say the, we are taking whether transverse electromagnetic mode would exist inside the structure that means for this mode the electric and magnetic field both are perpendicular to direction of propagation. That means they must lie in this plane, the cross sectional plane that is the plane of the paper. Now we know that magnetic field lines must close on themselves and all these magnetic field lines are now lying in this plane that means they must form the closed loops in this plane. So, the magnetic field lines in the transverse plane must look like that.

However, if the magnetic field lines are like this then we know that there has to be a current enclosed by this magnetic field lines. So, there must be a current flow something like this which is enclosed by the magnetic field lines then and then only this magnetic field lines can survive. So, there are two possibilities one is we have a conduction current which is flowing perpendicular to plane of the paper and that is enclosed by this magnetic field line, so they can survive or there could be displacement current which will be perpendicular to the plane

of the paper and that will be enclosed by the magnetic field lines, so the magnetic field lines can survive.

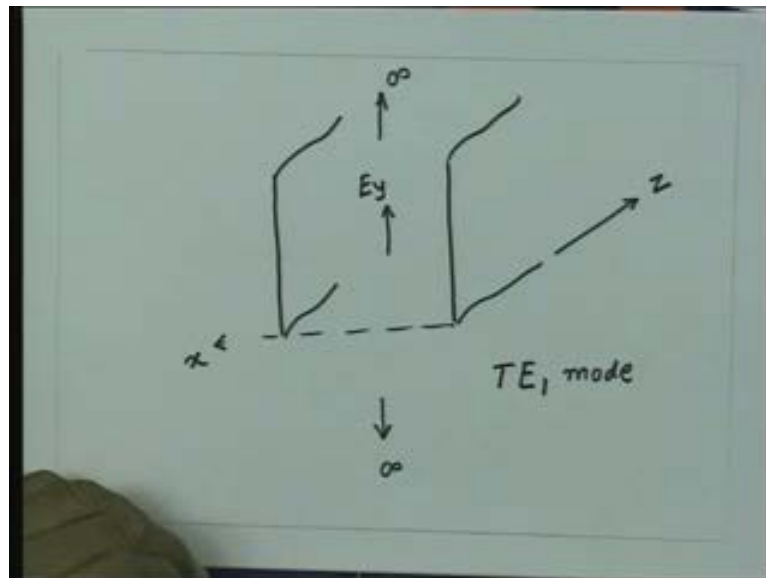
Since, we do not have any conducting medium inside this wave guide, this wave guide is completely hollow, it means it is filled by pure dielectric, there is no possibility of conduction current enclosed by this magnetic field lines. The conduction current is 0 inside the rectangular wave guide, so only possibility which can exist with we have displacement current to support this magnetic field lines and the displacement current must be flowing in that direction but the displacement current would require the electric field which will be going in that direction which we all denied for transverse electromagnetic mode but transfer electromagnetic mode we say the electric field also lies only with transverse plane that means it does not have a component perpendicular to the plane of the paper, if that is so then we cannot have the displacement current inside this wave guide which is in this direction. So, neither we have conduction current flowing this way nor we have displacement current flowing this way, so there is no current which is flowing perpendicular to the plane of the paper and if there is no current that cannot magnetic field lines because by MPS law this magnetic field lines must be related to the current enclosed. So, that means these fields which are lying in a transverse plane they cannot exist because there is no current to support these magnetic field lines that means this mode, the transverse electromagnetic mode cannot exist inside the rectangular wave guide.

So, this mode TEM mode doesn't exist inside this wave guide. There one can ask the question how was it existing in the wave guide which is the parallel thin wave guide and before you get into that question let us first take the parallel plane wave guide as a limiting case of the rectangular wave guide. So, if I take this rectangular wave guide in which the TE_{10} mode is existing that means electric field is like this and if I make this B is equal to infinity, if I push this wall to infinity essentially I will get a structure which will be the parallel plane structure, this plane and this plane wave is going to traveling in the Z direction and these two walls are pushed to infinity, so as a limiting case of the rectangular wave guide by pushing these two walls to infinity, I can get the fields for the parallel plane wave guide.

And in this case since the electric field is like this and the wave is going to propagate perpendicular to the plane of the paper, this mode essential would correspond to the TE mode. So, we have now by pushing these things for TE_{10} mode, if I push this field it walls to

infinity then I will get a geometry which will be the parallel plane geometry and for this geometry, electric field is oriented like this so that will give me the transverse electric mode. So, what you are saying is if I take this wave guide and push it to infinity, so these are the two walls of the wave guide is my coordinate axis.

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This is the direction which is the Z direction, this is the x direction and I am pushing these two walls to infinity and the electric field now is oriented in this direction which is this way. So, I have a component which is E_y and I have the magnetic field which is H_x and H_z for the TE_{10} case. So, if I look at the fields which I had for TE_{10} , I have E_y component I have H_x component and I have H_z component and these fields were constant as the function of Y. Same thing we can get now for the infinitely extended wave guide in Y direction that if there are no boundary conditions to apply in this direction these fields are infinite then this field is constant in that direction that was the precisely the field we used to get for parallel plane wave guide. So, indeed we can take the transverse electric 10 mode, make this boundary to go to infinity but since we do not have any dependence of y here, what that means is these fields are the same fields as I would get inside a parallel plane wave guide for a transverse electric 1 mode. So, these fields are TE_{10} for rectangular wave guide but these exactly the same the explanation I have for TE_1 mode for a parallel wave guide.

So, we have a situation here which is TE_1 mode for which the fields identical, two these fields which are TE_{10} mode for the rectangular wave guide. So, here you have the magnetic

fields which are having X component and Z component then E_y will be in this direction. So, you are having now the Z magnetic field which is in this direction, so as the limiting case of the TE $1\ 0$ mode we can get the transverse electric mode, lowest order transverse electric mode which is T 1 mode and the fields will be exactly same as what we go for T $1\ 0$. The another mode which we had was the transverse electromagnetic mode for which the electric field was not tangential to the boundaries, it was perpendicular to the boundary. Magnetic field was tangential to the boundary and we saw that was the mode which was not dispersive and which traveled as if the conducting boundaries are not existing and that is mode which was the TEM mode.

So we had a situation like that if I take a parallel plane wave guide like that and if this is the electric field E and this is the magnetic field H then the wave is going to travel in this direction Z and then this wave travels without any variation of electric and magnetic fields that we saw earlier because neither H requires a boundary condition to be satisfied, this is tangential you can always surface currents nor the normal component of electric field needs any boundary condition to be satisfied, you can always have the surface charges induced to compensate for the normal component of the electric field. So, this mode which was the transverse electromagnetic mode was existing inside and now one can ask a question, if this was the limiting case of the rectangular wave guide, how come this mode exist in this but when we take the rectangular wave guide this mode doesn't exist. But one can argue since the magnetic field is in the direction and since this plane is extended in Y direction, one can say that is magnetic field lines essentially close at infinity and they enclose these conductors, these conducting boundaries which have the current flowing on them, the surface currents.

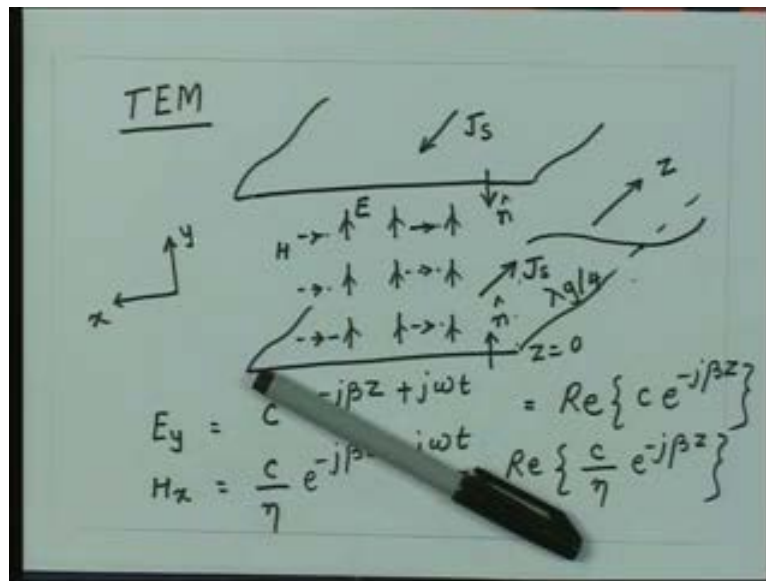
So, in the case of rectangular wave guide where these boundaries are finite, this magnetic field lines they have to close on themselves and that's why the current is not enclosed. So, this mode cannot exist inside rectangular wave guide but if I take a parallel plane structure then these magnetic field lines will close at infinity and they well enclose this conductors and that's why this mode can exist inside the parallel plane wave guide. This is the mode which is as we saw in case of two conductor system like a coaxial cable or transmission line, this mode propagates. So, whenever we have two conductor system, the lowest mode which will propagate will be TM mode, however if you go to the rectangular wave guide then the lowest mode which will propagate will be TE $1\ 0$ mode. So, we have very important conclusion to draw that whenever we have the hollow structure, hollow pipe and the wave guide, the

transverse electromagnetic mode cannot exist which is non-dispersive because it was a very special mode, this mode is not supported by the rectangular wave guide and that's why we have all those problems of dispersion and so on inside a rectangular wave guide. But that is the structure which is more physically realizable structure, you should remember that. The parallel plane wave guide is still a structure which is infinite in extent. So, we cannot realize this in practice, it is good for understanding but when we want to realize the structure in practice it is the rectangular wave guide which can be realized in practice not the parallel plane wave guide.

So, whenever we have a physical structure which is rectangular wave guide, we will always have a cut of frequency associated with that and we will always have the problems like dispersion and so on associated with that. With this understanding now let us try to see the currents which get existed on the walls of the wave guide which actually support this fields inside the wave guide, so whether you take parallel plane wave guide or you take rectangular wave guide what is the mechanism by which these fields are supported inside wave guide? What are the sources and the sources are nothing but surface charges and surface current which lie on the inner surface of the wave guide. So, as the wave travel even the surface charges keep moving to accumulate at different location as we will see little later and these charges and surface current support the electrical magnetic fields inside the wave guide which are responsible for carrying power inside the wave guiding structure.

So, what we will do now we will try to visualize first the fields which would be there inside the wave guide and then will try to visualize how the currents are distributed on the walls of the wave guide. So, let us take for the simplest case which is the TM case and the parallel plane wave guide.

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So, let us see I have a parallel plane geometry and let me Orient the planes, so these are the two conducting planes the energy is going to propagate in this direction and if I take the TEM mode, we saw the TEM mode the electric field is perpendicular to this. So, if I say this is my x direction, this is y direction then we had the electric field E_y which was some constant c to the power minus $j\beta z$ and we had a magnetic field which was a H_x which is c upon η e to the power minus $j\beta z$. If I visualize these fields is say if I really want to find out how these fields are going to be either the function of space and time inside the structure, first what we do we freeze the time. Remember all this quantities are intrinsically functions of time and they are having it harmonic variation as a function of time, so e to the power plus $j\omega t$ is implicit in all these terms.

So, as such these fields are going to vary as a function of space and time. So, if I stand at particular location the fields are going to vary sinusoidally as a function of time. If I freeze time we are bringing instantaneously look along the wave guide, I will see the field variation which will be given by that. So, essentially what we do to visualize these fields in three dimension first we do is freeze time that means make this quantity constant and then without losing generality we can say let make T equal to 0. So at that instant I want to see how the fields are distributed in space. Once I get those field distributions in space then we simply say that these fields will be moving with the velocity which is the phase velocity for the mode to then the let the field drifts inside this wave guide with the phase velocity. So, when we visualize these fields essentially we try to visualize the spatial variation of the field at some

instant of time and without losing generality we can take that time is equal to 0. So, if I take the T is equal to 0, if I freeze time then the field visualization will be simply a real part of this quantity which is real part of $c e$ to the power minus $j \beta z$ and this will give me again real part of c upon e to the power minus $j \beta z$. So, E_y has a variation which is real part of this which is c into cosine of βz , H_x will be having the same variation c upon e cosine of βz .

So, if I consider this point as z equal to 0, this variation is βz and the wave length which we have here or the phase constant is β , so the corresponding wave length let us call in general that is the guided wave length in the direction of wave propagation. So, this field has the period, special period which is equal to the guided wave length and at z equal to 0 this field is maximum. So, it is maximum here and it is not varying as the function of x or y , so the fields are constant everywhere. So, the field is varying as a cosine function along the z direction. So, it is maximum here, so if I take here this point $j z$ equal to 0, so it is maximum and then it goes like that either I move along the z direction like a cosine function where this is 0, this quantity will be λ_g by 4 that this function will go to 0. If I go again λ_g by 4, this function will become negative and so on.

So, this field now I can visualize as the electric field which is constant everywhere, so this is the field distribution for the electric field is like that which is same everywhere and so on. And the magnetic fields are horizontally oriented and there again having the same amplitude all across, so this is the direction of the magnetic field. So, though direction is taken appropriately so that $E \times H$ gives me the power flow which is in this direction. So, this is magnetic field which is everywhere as distributed, so this is my H vectors and this my E vectors. And at to maximum here, as I move to λ_g by 4 along the direction of wave propagation these fields will go to 0 then again they will reverse the direction after λ_g by 4, go to maximum when z becomes equal to λ_g by 2 and so I got a variation which is if I look like that, if I turn it electrical field is maximum here slowly reduces, goes to zero, changes a direction again increases maximum negative. So, start from here goes to 0, changes direction increase again maximum that's the where electrical field is distributed. You can see here the rod shear which is standing of different heights, it is maximum here at z equal to 0, the height of the rod goes to 0 at λ_g by 4, the direction of the rod is reversed. And again the amplitude becomes maximum, when I go a distance of λ_g by 2.

Same thing happens here for the magnetic field lines which are now like that, so they are stacked. This will look as if you are having a layer of the magnetic fields which are oriented this way as stack and again there variation is will be exactly same that when this field goes through 0, the magnetic field also will go to 0 and so on. So, it requires little imagination to really visualize these fields but with little practice one can definitely see how the electric fields and magnetic field are distributed inside the wave guide.

Now, if we know that the magnetic field is like that the current which is going to flow on the surface of this conductor is related to the magnetic field, tangential component of the magnetic field. The $\mathbf{N} \times \mathbf{H}$ gives me the surface current on these conducting walls and since we are considering here the ideal conductors, essentially if I calculate $\mathbf{N} \times \mathbf{H}$ that is the current which is truly confined to the surface of this parallel plane wave guide. So, if I consider this surface then the normal will be coming outwards, so this is my normal unit vector whereas if I consider this plane then the normal which will be coming out of the conducting surface will be this now.

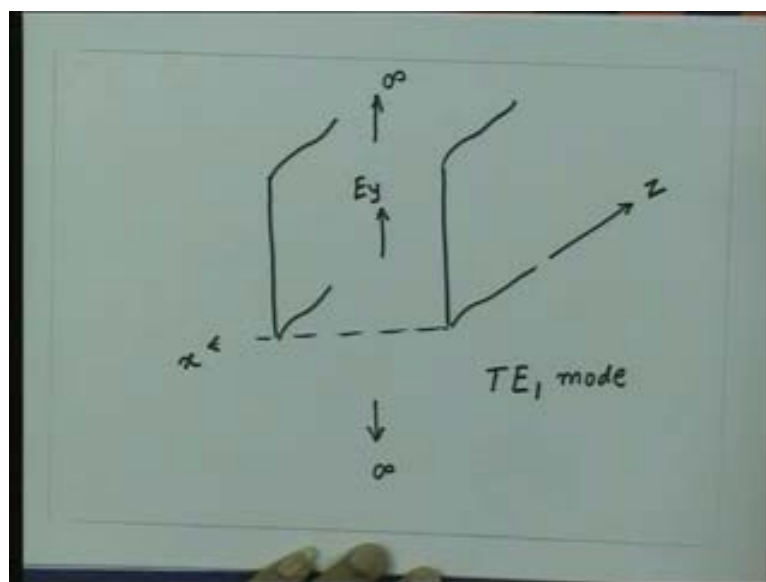
So, the unit vector outward normal for the lower plane will be going upwards, the unit normal for the upper plane will be going downwards and now you can calculate $\mathbf{N} \times \mathbf{H}$ everywhere. So, this is direction of \mathbf{H} , this is \mathbf{N} , so if I calculate $\mathbf{N} \times \mathbf{H}$ at the point I will get the direction of the surface current which will be along the direction of the wave propagations. Similarly, say on this surface the current will be going in this direction because I get $\mathbf{N} \times \mathbf{H}$ whereas if I go to the this surface then I will get $\mathbf{N} \times \mathbf{H}$, \mathbf{N} is now downwards \mathbf{H} is this, so I will require $\mathbf{N} \times \mathbf{H}$ which gives me the current which will be coming out.

So, on the lower surface I get a current which is going this way, this is my surface current where on this surface the current will be flowing this way which is \mathbf{J}_s and it will be having a same variation as the variation of the magnetic field that means it will be maximum here after the distance of $\lambda/4$ this current will go to 0 and so on. So, in a two conductors system, it gives you the current flow in the direction in which the wave is propagating. I have a current flowing this way, I have a current flowing this way and precisely that's what we are essentially used to that when we have a two conductor system like a coaxial cable, we connect a voltage source and the current goes inside the conductor, the current returns by what is called as a ground path. So, we see that the current goes inside from one terminal and

current comes out side from the other terminal. So, in that situation which is like a two conductor system, the direction of the current flow which we have for this mode, TM mode keep that mind is same as the direction of the wave propagation. So, the current is going, current is returning from here.

Question one can ask is if the wave is propagating in this direction, is it always true that the current has to flow in the direction of the wave propagation and invariably we get the answer which is wrong and that is since we always discuss the transverse electromagnetic mode that's what we are used to when we go to low frequency circuit immediately we jump to the conclusion that yes since the wave is moving in this direction, the power is flowing in this direction, the current must flow in that direction.

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Let us look at the parallel plane wave guide but let us take the mode which is TE 1 mode and let us see what will be the direction of currents in field in that wave guide. So, let us consider the structure which we have got this is the T 1 mode and this is parallel plane wave guide. As we saw that the fields for the parallel plane wave guide will be identical to this, so firstly the electrical field will be y oriented, they will have variation which will be next direction and they will be varying again in z direction with phase constant beta so in this direction if I look at the field variation and if I write down the expression for this, I will get again in z direction also.

However to visualize these fields, as we did in the previous case let us take amplitude of this field that is real part of this quantity and plot that as a function z, x and y, you will get a three dimensional picture of the fields. Before we do that however let us try to take this j and represent that along with this because j is e to the power j pi by 2, so minus j will be e to the power minus j by 2.

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$$E_y = A \sin\left(\frac{\pi x}{a}\right) e^{-j\beta z - j\pi/2}$$

Instant field: $\text{Re}\{E_y\}$

$$= A \sin\left(\frac{\pi x}{a}\right) \sin \beta z$$

$$= A \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{2\pi}{\lambda_g} z\right)$$

$$\text{Re}\{H_x\} = B \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{2\pi}{\lambda_g} z\right)$$

$$\text{Re}\{H_z\} = C \cos\left(\frac{\pi x}{a}\right) \cos\left(\frac{2\pi}{\lambda_g} z\right)$$

So, if I take this field expression and write that I get this quantity E_y that is equal to let me put this whole quantity as some constant, at the moment we are only interested in finding the variation of the field in X and Y, so let there be some constant here expect j we are going to put at this point. So, let us say I have some constant here some A sin of pi x by a and I write here e to the power minus j beta z and I take this minus j up so this will be equal to minus j pi by 2. So, if I want to get the instantaneous field as a function of x y z at a real part of this quantity, so the instantaneous value the electric field that will be real part of E_y that will be amplitude A sine of pi x by a. Cosine of this quantity, this quantity and that will be equal to the sine of beta times z where you have a phase difference here of pi by 2. So, you have here sine of beta into z which we can write down explicitly in terms of the guided wave length. So, this we can get is A sine of pi x upon a sine of 2 pi by lambda g into z. Same thing I can do for this magnetic field also, so this quantity again there is omega epsilon, the omega nu.

So, I can say this is another constant for the magnetic field, so H_x I can write down the instantaneous value that will be real part of H_x which will be some constant B sine of pi x

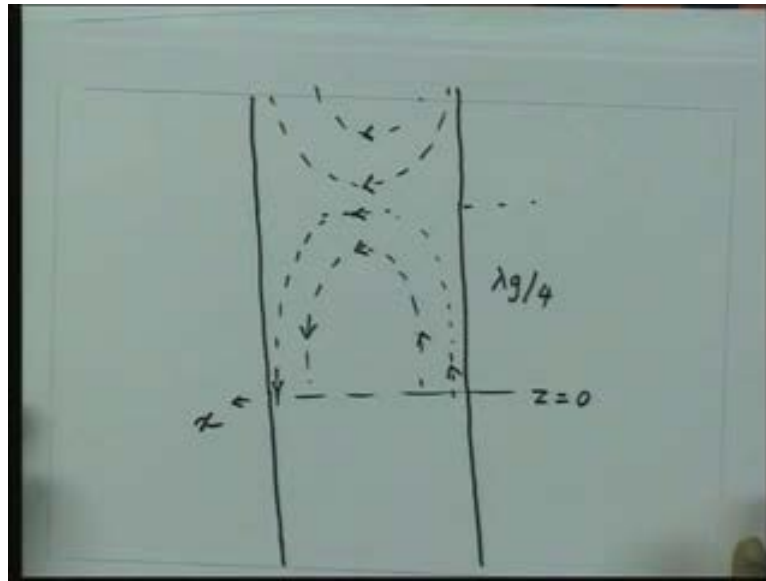
upon a and this quantity is same again we can take a minus j up there, so this will be sine of 2π by λg into z . And I can get again the instantaneous value for the magnetic field z component and there is no j here now, so if I take real part of this, this will be simply cosine of βz so the real part of the H_z that will be equal to is constant $C \cos$ of πx upon $a \cos$ of βz , this is 2π by λg to z . So, these are the fields which are now if I freeze time and if I take that T equal to 0 then at that instant the field along the wave guide will be given by this expression. So, in the z direction as we can see the fields are sinusoidal with a period, special period which is λg however these two are in quadrature that means wherever H_x is maximum, the H_z is 0 and wherever H_z is maximum H_x will be 0.

So, in space we are having two components now, the H_x component and the H_z component and H_x component is having a sine variation. So, if I take this point z equal to 0, H_x is 0 at this location but H_z is maximum at this location. If I have go a distance of λg by 4 on this, at that location H_x will be maximum but the H_z is will go to 0. So, if I see from the top it will appear here the H_x was 0, only H_z was here. As it is moved to a distance of λg by 4, the H_z becomes 0, only H_x become maximum so the magnetic field totally become like this along this direction.

As I move further again by λg 4 again H_z will become maximum, H_x will come 0. So, what you find that here we have a function which is cosine with that means if I take this as plus direction, so here I have a magnetic field like that. On the opposite wall magnetic field will be this the cosine function, so z equal to this quantity, this variation as a function of x . If I plot this, this is the one which in the x direction is going to be like this, z direction the variation is periodic with λg but in the x direction this is maximum at x equal to 0, at x equal to a with opposite sign and 0 at the center. So, the magnetic field lines are maximum here and no component of the magnetic field H_x at this location, so the fields are this.

If I go to the distance of λg by 4 in this direction, at that location if I see here the H_z would go to 0, H_x will be maximum but the H_x is a having variation of sine of πx upon a . That means H_x is maximum at this location but it is not maximum on the walls, this function is a sine function. So, it is 0 here, 0 here and will be maximum here and that will be the direction for H_x which would be like that.

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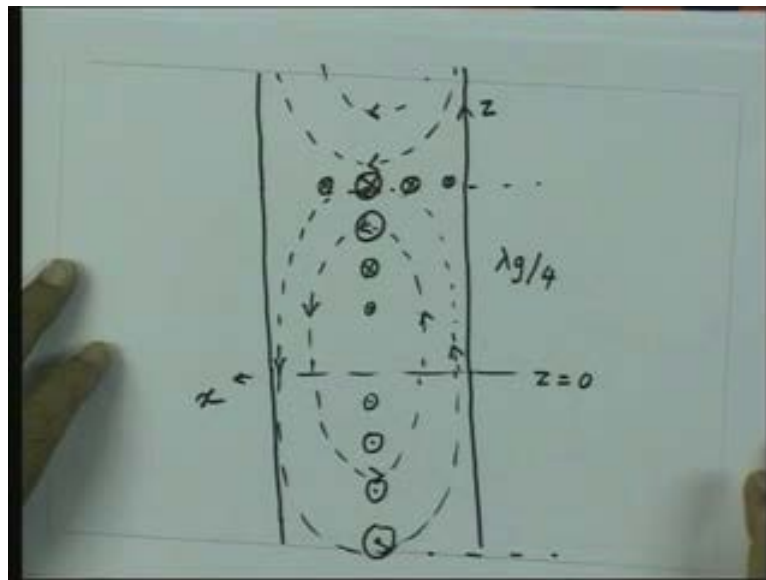


So, if I see from the top I see situation like this for the parallel plane wave guide, so if I am seeing on the top like that the magnetic field is z equal to 0, the magnetic fields are like that, like that here. When I go to distance of $\lambda_g/4$ this thing has gone to 0 and H_x is become maximum so that is oriented in this direction. Now it is matter of a little imagination since we know that magnetic field lines close on themselves essentially we have a magnetic field loop which is created like this, so we got a magnetic field lines which will go like that. And if I go further $\lambda_g/4$ from here the direction will be reversed, if I go further in this direction, this direction is x remember so again I get the magnetic loop which will be like this and so on.

If I complete this if I now say the other way a wave guide which is running from minus infinity to infinity, essentially I will get the loops of the magnetic field lines which will look like that where this separation will be equal to $\lambda_g/2$. So, if I look at the wave guide which will look like that this is the parallel plane wave guide, the magnetic fields lines look like rolled carpets which are stacked inside the structure and they are of infinite length which are perpendicular to the plane of the paper. That's the way the magnetic field lines will be distributed. What about the electrical field? The electrical field has a variation in z direction which is same as this but it is oriented in y direction, so if I consider this it is having sinusoidal variation in this direction but oriented this way.

So, if I see from the top then the electric field lines will be perpendicular to the plane of the paper and behavior of this E_y and H_x is identical that means wherever H_x is maximum, E_y is going to be maximum only thing it has variation, it is sinusoidal variation so it has identical variation $2 H_x$.

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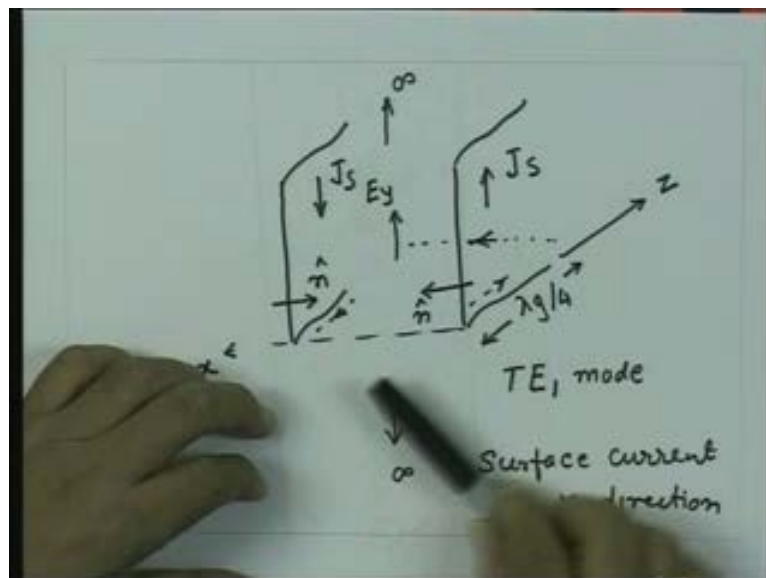
So, if I look at the H_x component which is this component, here is H_x component which is maximum, so the electric field also will be maximum at this location but electric field is always oriented in y direction. So, I have the electric field which will be like that and if this is the direction positive direction for z in which the wave is propagating again you can have E cross H. So, if this is direction of the magnetic field the electrical field should be going inwards so E cross H gives me the pointing vector so that is direction of the electrical field and this electric field reduces to 0 at this location, so I have electric field becoming lesser and lesser as I go this direction. Similarly, it's becoming lesser and lesser because the tangential component should become 0 so this becomes less here, less here and so on.

Again where I go on this side the electrical field now will be coming outwards and amplitude will increase again, so here the size of the circle tells me the strength of the electrical field. So, the electric field will be distributed maximum where this H_x component is maximum, so this is more like rods which are inserted in the rolled carpets that is the electrical field vectors. So, if we want to visualize in the three dimensional kind of fields, the electric field will be the stacking of the rods of different diameters where the diameter represent the

strength of the electrical field and the magnetic field will be like stacked rolled carpets which will be like that.

Once we get this magnetic field things which is now a rolled carpet which we have got which we have seen from the top the magnetic field lines like that, now we can ask what kind of currents are going to flow in this. Say now the currents will be related to the tangential component of the magnetic field on the walls and the tangential component of the magnetic field which is this on this wall, these two walls is only z component, on this wall there is no x component.

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So, on this wall the unit normal will be going inwards so this is my \hat{n} , for this wall this is \hat{n} . Here the magnetic field is going tangential to this which is in this direction, z direction, x direction magnetic field is 0. So, on the walls if I see I have only magnetic field component which is z component, if I calculate $\hat{n} \times \mathbf{H}$ this is \hat{n} and this is \mathbf{H} . See, if I go from here to here the $\hat{n} \times \mathbf{H}$ in this direction I will get now the current direction which will be tangential to this surface current that's what we are talking about but that will be now flowing in the y direction because normal is in x direction and the magnetic field is in the z direction, so $\hat{n} \times \mathbf{H}$ if you take that current flows in the y direction which is this direction.

So, we have now the surface current which flows into this, so if I take again and this is my unit vector, this is my magnetic field which is like that okay. I take $\hat{n} \times \mathbf{h}$ which will be

going from this to this, I get the direction of the current which will be surface current which would be like this, it is J_s and this is J_s . So, very important note now is compared to the TEM case that's the surface current is going to flow in the y direction that is very important. So, we have here surface current in y direction again it will have a variation which is sinusoidal in z direction but there is no current flow in z direction that is the important thing to note but the wave is traveling in the z direction, if the wave is traveling in z direction the power is flowing in z direction.

So, what we now find something very interesting that the power flow there is no component of current, surface current in this two conductor system in the direction of the net power flow. The current flows in this direction but the power flow in this direction, so the notion which you have at low frequencies that's in the power is going inside the system, the current must be flowing in the same direction that is completely wrong in fact the direction of current flow and power flow have nothing to do with each other. The current may flow in some arbitrary direction and the power may flow in some other direction. In fact it will be also immediately clear to us that where is the power flowing, where is power. The ideal conductor doesn't carry in any power inside; the power is only between these two conductors. The power is carried by the fields which are trapped between the conductors that's what is carrying power to support this field we required the currents, so the currents are not carrying power. The power is carried by fields so there is no reason why the current should flow in same direction which the power is flowing.

However as I have mentioned at low frequencies we normally have a wrong notion that since the power is flowing inside the circuit, the power is carried by the current, the power is carried by the charges. So, we get a wrong picture that the currents have to flow because the current is going to carry power in fact this is now a better understanding which says that power flow is because of the fields and not because of the current. So, the current may flow in some arbitrary direction and in this case you can see it actually flows perpendicular to the direction of the power flow. So, the power flows in z direction and the current flows on the surface of these two conductors which is in this direction. So, the notions normally which we will have at low frequency circuits, they come from the transverse electromagnetic wave though we don't say that explicitly there because that time when we talk about a simple circuits, we do not get into the complications of the field distributions but intrinsically we assume that the field which are carried by the electrical circuit is a transverse electromagnetic

field, so we have certain notions which we build for the electrical circuit and they come essentially from the natures of transverse electromagnetic wave.

As soon as you make a departure from the transverse electromagnetic wave to a transverse electric or transverse magnetic then all those notions completely break down and then we get much global picture of propagation of electromagnetic waves and the currents and the distribution of charges and so on at for various configuration. So, with this understanding now for the current flow on this parallel plain structure which is rather simplest structure, now we can discuss the field distribution inside the rectangular wave guide which is more practically realizable structure and then again we will see the current flow on the wave guide surface for rectangular wave guide and then we will have little more advance things like calculation of losses and other things for rectangular wave guide.

So, let me summarize what has been discussed here essentially we saw that the transverse electromagnetic mode cannot exist inside a rectangular wave guide and that we showed from the physical arguments then we also showed that if you take a rectangular wave guide and push one of the dimension to infinity then the field we get for rectangular wave guide, they are identical to what we would have got for parallel plane wave guide. Then we developed a mechanism of really visualizing these fields inside these wave guides.

So, we saw two cases one was the transverse electromagnetic wave inside a parallel plane wave guide other was T₁ mode inside a parallel wave guide and then we saw something interesting that the direction of the current flow on the surface of the wave guide need not be same as the direction of the power flow. The direction of the current and the power flow are same for only transverse electromagnetic case. However if you go to general mode then the current might be flowing in different direction and the power flow which is due to the fields trapped between the two conducting boundaries could be in some other direction. So, in next time we discuss in detail, the fields and the power flow inside a rectangular wave guide.