Transmission Lines & E. M. Waves
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Lecture No. # 39

We are investigating propagation of an electromagnetic wave inside a hollow pipe with rectangular cross section. We call that structure as rectangular wave guide.

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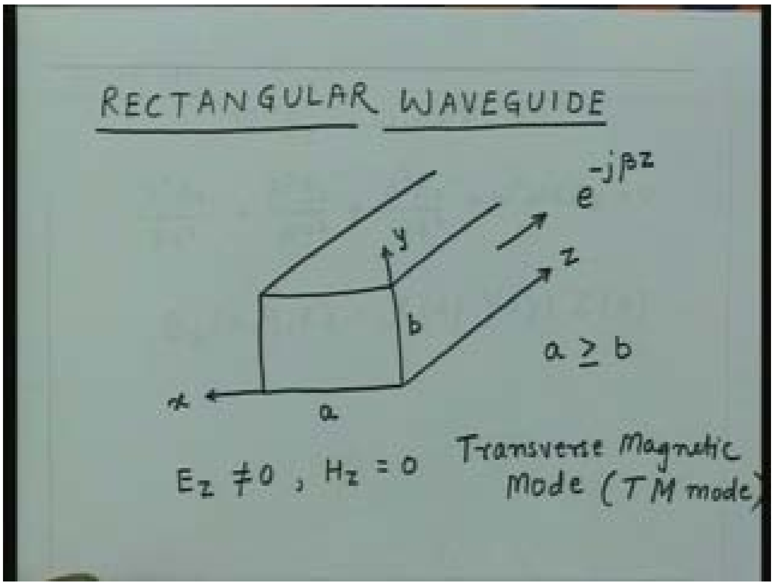

So, last time we defined certain conventions on rectangular wave guide. This is the rectangular wave guide, the energy flows along the length of this pipe and then we oriented the coordinate system such that the x axis is along the broader dimension of this wave guide and the y axis is along the shorter dimension of the wave guide. And then by definition, we took this a which is greater than or equal to b which is the height of the wave guide. And then by solving the wave equation, essentially we got the expression for the electric and magnetic fields and specifically we investigated what is called the transverse magnetic mode for which E_z is not equal to 0 and H_z is equal to 0. And then we had drawn certain important conclusions about this mode which is transverse magnetic mode and that was that without having the field variation in the transverse direction, you cannot have the transverse magnetic mode.

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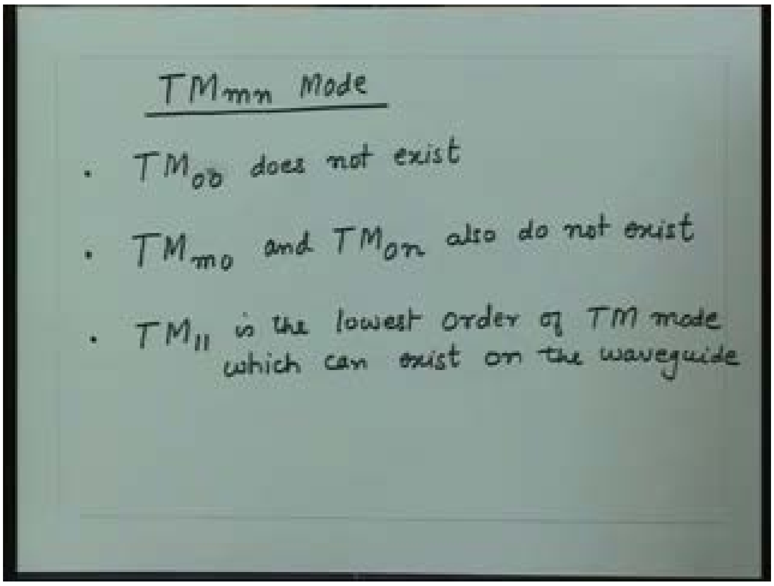

So, we got transverse magnetic mode TM mn where m and n give the indices in the broader and shorter dimension of the wave guide. So, the first index tells me the number of half cycles which are going to be along the x direction which is along the broader dimension of the wave guide and n tells me the number of half cycle variations along the shorter dimension that is the y axis of the coordinate system. And then we saw that the TM 0 0 does not exist that means if I take m and n both indices zero which means no field variation either in x direction or in y direction that means no field variation in the cross sectional plane. If we take that situation then these kinds of fields cannot exist inside this rectangular wave guide.

We also saw that not only that no variation in any direction but even if the field is constant in any of the directions either x or y even then the field cannot exist. So, essentially what that meant was that we must have at least one half cycle variation in x direction and one half cycle variation in y direction for existence of the field. And that's what we got what is called the lowest order transverse magnetic mode which we got is TM 1 1 mode which can survive on a rectangular wave guide structure. With this understanding, then we now want to investigate the other type of mode that is the transverse electric mode for which…

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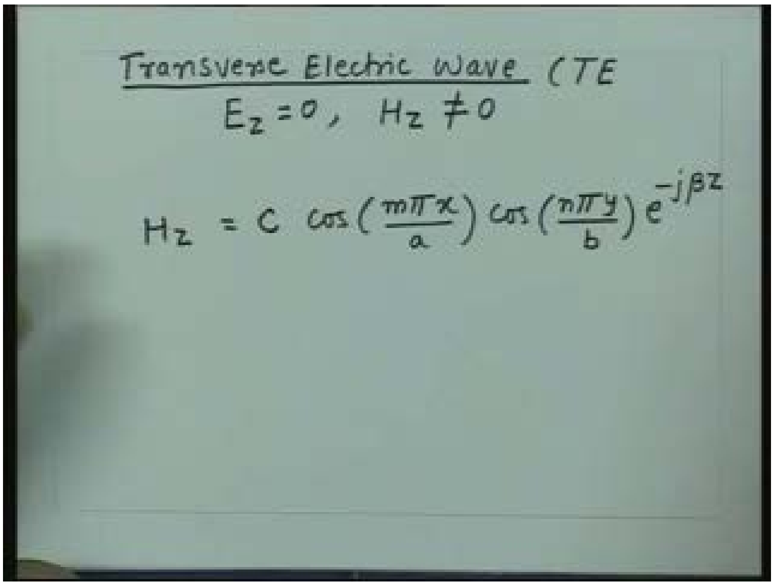

Now, since the field is transverse electric the E_z is 0 but H_z is not equal to 0 and then as we explained last time that using the observation which we have got from the transverse magnetic mode that the tangential component of magnetic field becomes maximum on the surface of the conductor and the field must have the sinusoidal variation in both the dimensions x and y, we can get an expression for H_z that is some constant cosine of m pi x by a cosine of n pi y by b e to the power minus j beta z.

Again, the m and n define the indices that means the number of half cycle variations in the x and y direction that means the broader and shorter dimension of the wave guide. So, as we did in the case of transverse magnetic mode, we can put these two indices along with TE, so even the transverse electric mode is designated by TE mn mode. I had also mentioned that this expression can be obtained again in a routine fashion that means you take this condition substitute to the wave equation, solve for wave equation, get a general solution, find out the transverse component, match the boundary condition and you will get the expression for the longitudinal magnetic field.

Now, on the line similar to the transverse magnetic mode we can ask what kind of indices are required for existence of these fields. So, firstly we can note that in this case if m is equal to 0 and n is equal to 0 that means the mode is TE 0 0, the magnetic field now is not zero, it is constant. If you recall in transverse magnetic case, the E_z was identically going to 0 when both the indices were 0 but in this case when both the indices are 0, this magnetic field doesn't go to 0, it is constant.

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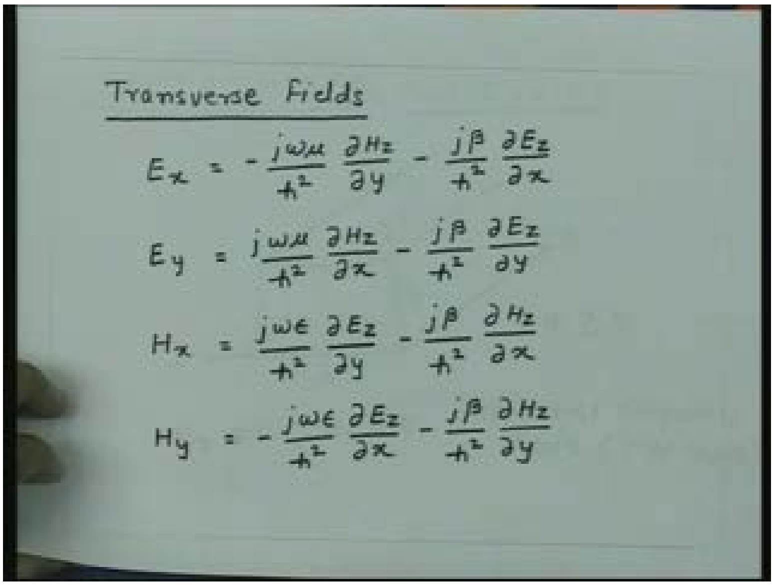

However, if you recall the transverse fields are expressed in terms of these longitudinal fields E z and H z, these are general expressions but all these transverse field involve the space derivatives. So, either you have a derivative with respect to x or you have a derivative with respect to y. So, if I have a field which is constant it doesn't vary as a function of space that's what m equal to 0 and n equal to 0 would mean that H z is constant. Essentially, all the space derivatives are zero and that means all the transverse fields will identically go to 0.

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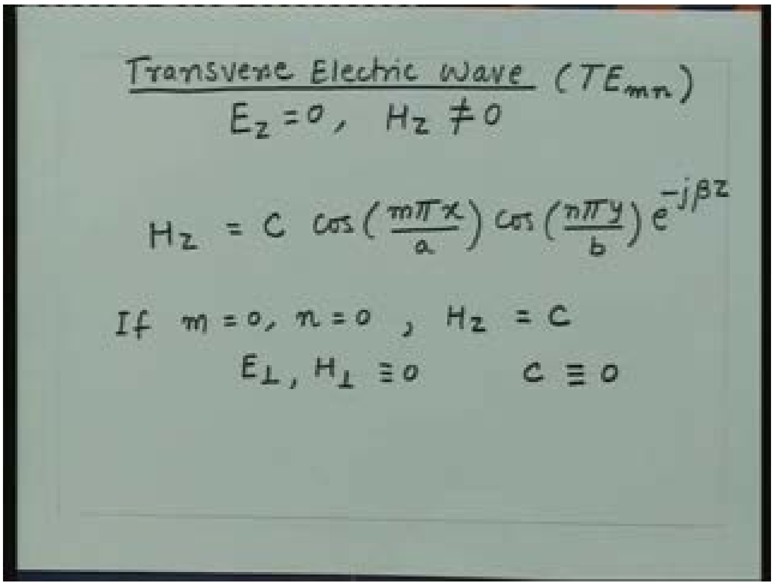

So, if you consider a situation that if m is equal to 0, n equal to 0 then H_z is constant but since the transverse field involve the space derivatives, all the transverse components of electric and magnetic field will identically go to 0. So, it will mean that E transverse and H transverse will be identically 0 because they derive the space derivative of the longitudinal component. So, that means in this situation when m is equal to 0, n equal to 0, we have the magnetic field but there is no electric field because E_z was already 0 as we have taken by definition. So, we are having a magnetic field without having electric field but what we have seen for time varying fields this cannot happen because time varying electric and magnetic fields are coupled.

So, if this electric field goes to 0 then identically the magnetic field also must go to 0 because the time varying magnetic field cannot exist without electric field and vice versa. What that means is that in this situation, this constant c must be identically equal to 0. So, in this situation the c must be identically equal to 0 that means the mode TE 0 0 cannot exist now because this quantity is identically zero. So, these fields cannot survive inside the rectangular structure, so we make again important observation about transverse electric wave that the TE 0 0 mode cannot exist.

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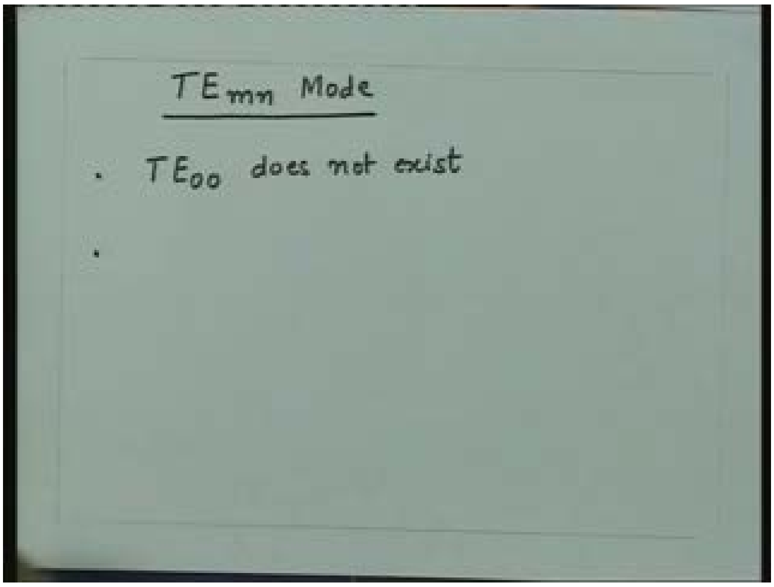

So, we can write down now the observation for TE case, TE mn mode. Firstly, TE 0 0 does not exist, second conclusion now we can see from here that in case of TM case when both the indices were zero again the fields were identically going to zero.

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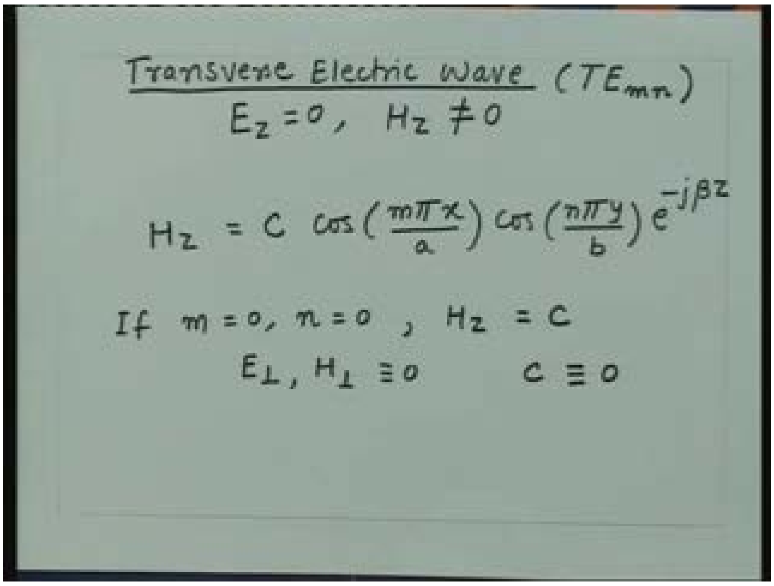

However, that is not true in this situation because if one of the indices is zero then you have this function which will be non-zero, so H_z will be non-zero and also it will be having a variation in space. If I take n equal to zero then H_z will be a function of x, if I take m equal to zero then H_z will be a function of y. So, the space derivatives exist, H_z exist, so the transverse field exist and that's why having one of the indices zero the field can exist that means TE m 0 modes can exist, similarly TE 0 n mode also can exist.

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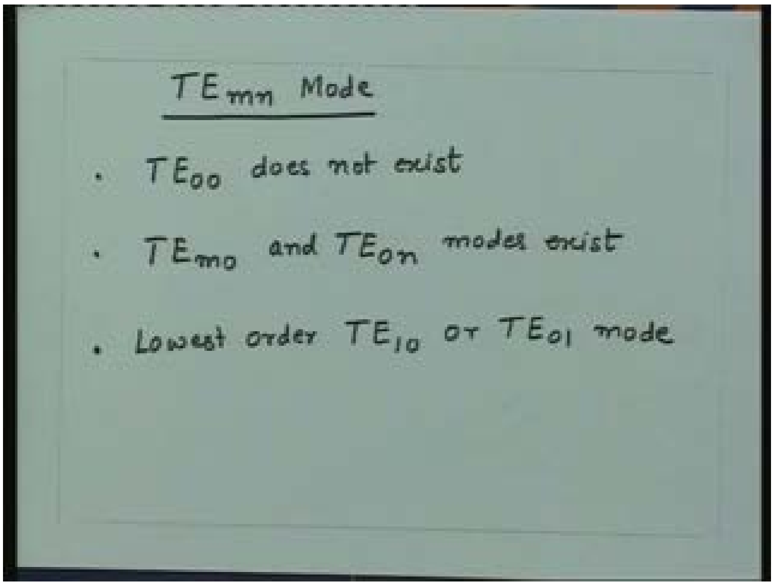

So, in this case we have important conclusion that the TE m 0 and TE 0 n modes exists, that means now the field should have variation at least in one direction it may be constant in other direction that means if I take n equal to zero that means the field will not have any variation in y direction and it will have number of half cycle variation depending upon the value of m. So, the field may be constant in one of the directions and it may be varying sinusoidally in other direction. These kinds of fields can exist now for the transverse electric case.

So, if I now ask what are the lowest order modes which can exist, so we can get now? The lowest order index if I take m 1 and n 1, the lowest order would now corresponds to either TE 1 0 or TE 0 1. So, now we have got three lowest order modes, transverse electric if I take the lowest index m and n, I get TE 1 0, TE 0 1 and for transverse magnetic I have TM 1 1.

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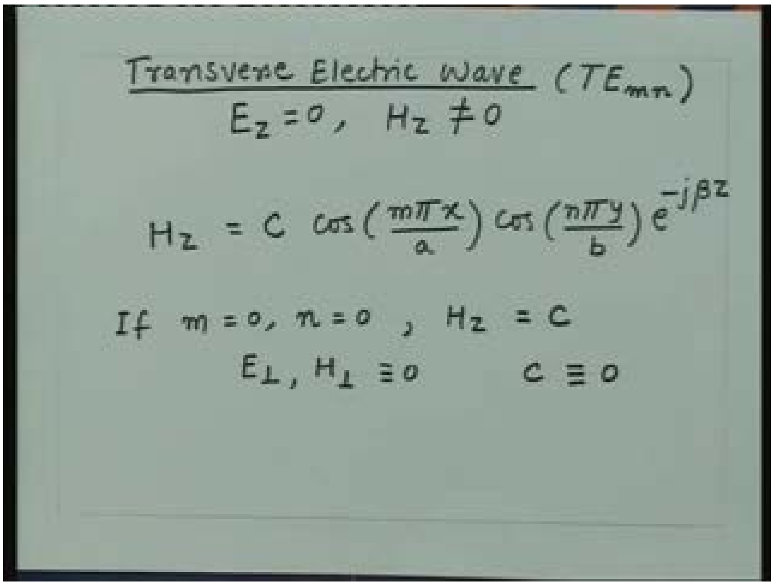

If I take this now magnetic field and substitute into the wave equation or if start with the wave equation and as we did for transverse magnetic case, we got a dispersion relation, we will get identical dispersion relation in this case also.

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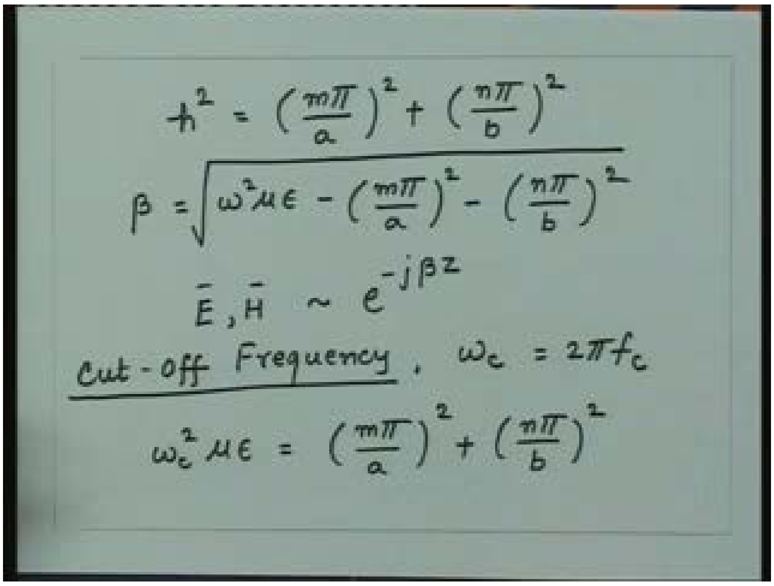

So, in this case also as we got in case of transverse magnetic case, we will get this quantity h square that will be m pi by a whole square plus n pi by b whole square. And as we got in the previous case the phase constant in the z direction which is beta that is omega square mu epsilon minus m pi by a whole square minus n pi by b whole square, square root of this quantity. In parallel pane wave guide we had called this beta bar, however in this case since the net wave propagation is going to be in the z direction. Just for simplicity we have dropped the sin bar but in this case the beta essentially means the phase constant in the z direction or along the wave guide.

Now as we defined the cut off condition in case of parallel plane wave guide, the same thing we can define in this case also that all the E and H field variations which we have they vary as e to the power minus j beta z. So, it will represent a travelling wave provided this quantity beta is a real quantity. If I take a frequency for which this quantity is greater than omega square mu epsilon then this quantity inside the square root will become negative and beta will become imaginary. If beta becomes imaginary then this quantity doesn’t represent now a travelling wave, it will simply represent exponentially decaying fields in the direction z that means along the wave guide and essentially the wave propagation will seize. So, for propagating wave it is essential that the frequency must be higher than certain value so that this quantity is a real quantity.

As we discussed in case of parallel plane wave guide that the frequency where this transition takes place that means from the travelling wave to the decaying field, we call that frequency as the cut off frequency of a mode. So, as we can see for different values of m and n, we will have different frequencies where these transitions will take place and a transition will take place essentially when beta is equal to zero then this quantity is equal to zero. When it is positive you get beta real, so you get a travelling wave, when this quantity is negative you get beta imaginary so you get a decaying field.

So, we define now this condition what is called the cut off frequency of a particular mode and that frequency is the frequency at which this quantity becomes 0. So, let us say this cut off frequency is given by omega c, angular frequency or this is 2 pi into the cut off frequency f_c. So, by substituting this omega c inside this, essentially I get omega c square mu epsilon that is equal to m pi by a whole square plus n pi by b whole square. I can write down explicitly for the frequency, so I get the cut off frequency f_c that will be 1 upon 2 pi square root mu epsilon m pi by a whole square plus n pi by b whole square, square root.

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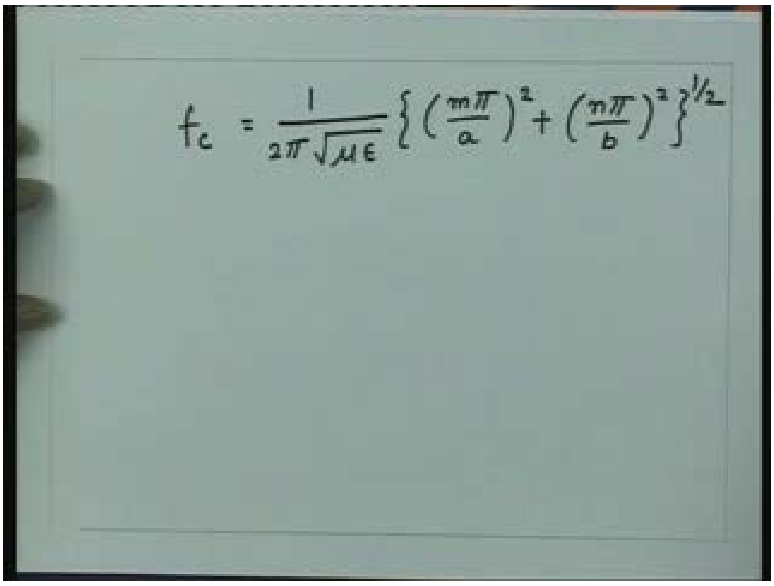

So, now knowing the mode order that mean knowing the value of m and n and a dimension of the wave guide, I can find out the cut off frequency for a particular mode. The dispersion relation now can be written in terms of this quantity because this quantity is nothing but omega c square mu epsilon. So, many times we can write down as the dispersion relation which is beta is equal to square root of omega square mu epsilon minus this quantity which is nothing but omega c square mu epsilon.

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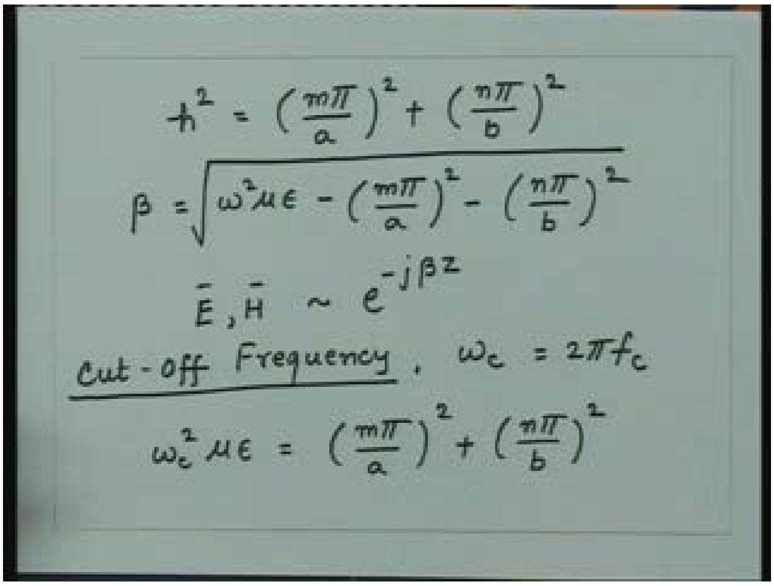

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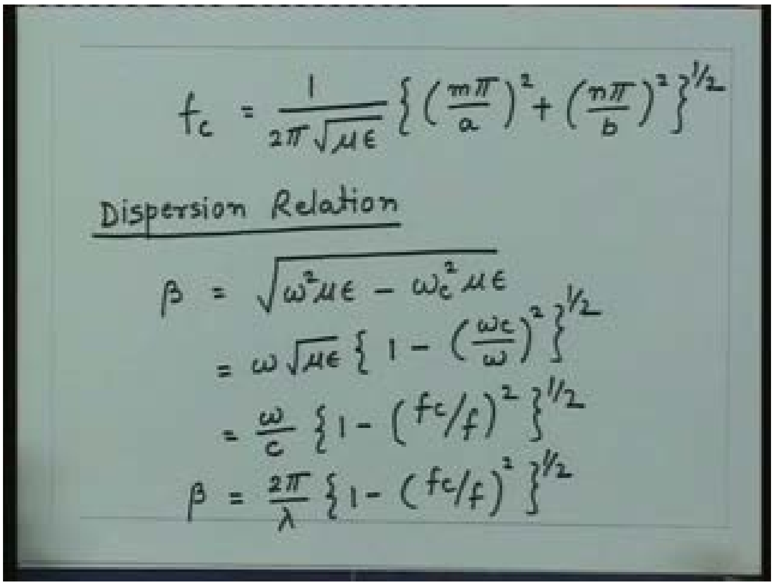

So, we can write this as omega c square mu epsilon. We can take this omega square mu epsilon common, so this will become omega square root mu epsilon 1 minus omega c by omega whole square or I can write in terms of the cut off frequency. Now noting that this quantity, square root mu epsilon is 1 upon the velocity of the wave in the intrinsic medium, so if I consider a medium which is filling the wave guide has permeability and permittivity mu and epsilon, then the velocity in that medium intrinsically will be 1 upon square root mu epsilon. So, this quantity is nothing but the velocity of light in that medium which is filling the wave guide.

So, we have here omega divided by c 1 minus and I can write omega explicitly in terms of the frequency, so this will be cut off frequency by frequency square, square root. And omega by beta if you write this is omega is 2 pi into frequency and then c upon frequency is the wavelength in the intrinsic medium, so this quantity we can also write as 2 pi by lambda into 1 minus cut off frequency by frequency whole square, square root. This is your phase constant. Now, this is the phase constant for the wave guide in the z direction, so now imagine that I have this structure for which the quantity which I can measure is the variation of the electric field along its length that means if I take some probe and move along the length of the wave guide, I will see the separation between two points, two maximize which will be separated by a certain distance and that will be related to the phase constant of that wave along the direction of the wave guide.

That means this quantity beta whatever we have here for this particular mode, this quantity is 2 pi divided by lambda which I am going to measure on that wave guide. This lambda is certainly not same lambda which intrinsically the wave has in an unbound medium. That means if I know the properties of the medium, mu and epsilon and if I imagine this medium to be infinite, then I get a wavelength what is called lambda which is the velocity of light divided by the frequency.

However, if I take a structure like a wave guide certainly I am not going to measure this lambda anywhere, what we are going to measure is this phase constant or any equivalent wavelength which will be related to this beta which is the phase constant. So, we know by definition that if I know the phase constant, I have this quantity beta which by definition is 2 pi divided by wavelength but this wavelength now is not the wavelength in an unbound medium, this is the wavelength which we are going to measure along the length of the wave guide or this is the wavelength which is for that guided electric and magnetic field distribution inside the rectangular wave guide. That is the reason we call this wavelength as the guided wavelength and we put a suffix to this as g where this quantity is called the guided wavelength.

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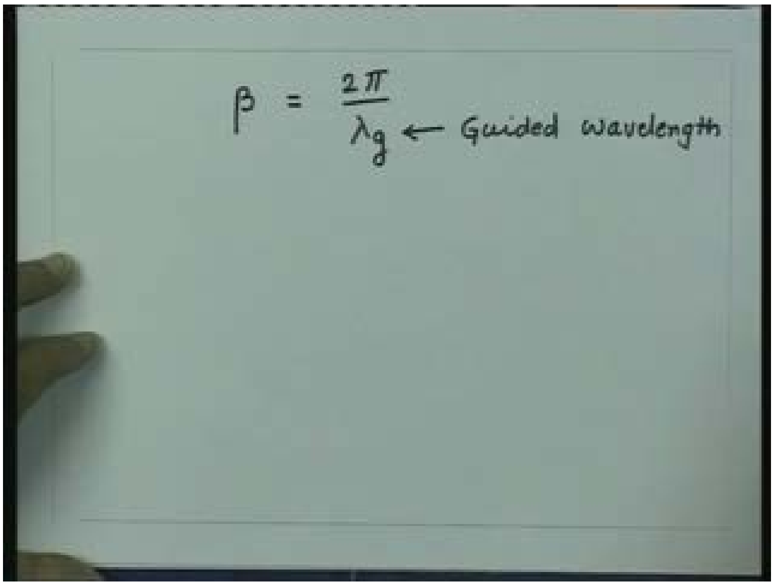

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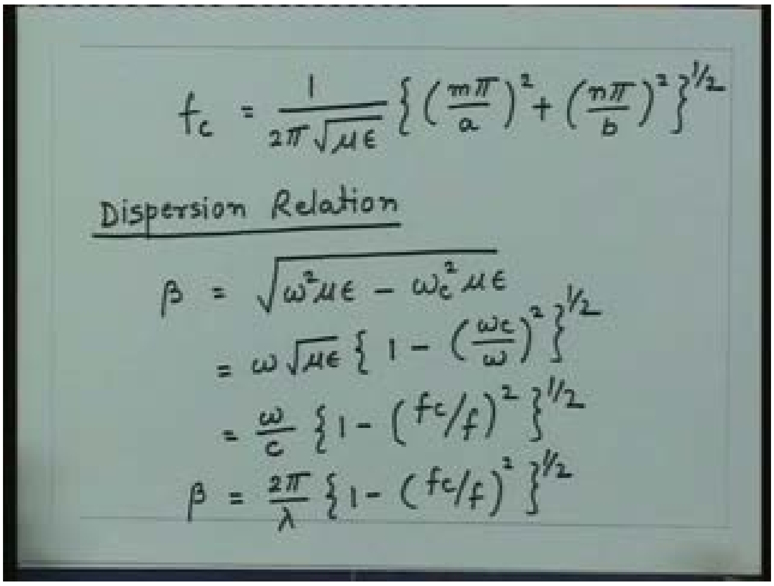

So, see what we have done. We got this quantity beta from our analysis, whatever that quantity beta is if I take 2 pi divided by that beta we get a number and that number essentially tells me the effective wavelength along the wave guide in which the wave is going to travel. So, on a physical structure like a rectangular wave guide, the meaningful parameter is the guided wavelength and not the intrinsic wavelength because this wavelength we are not going to measure right along the wave guide.

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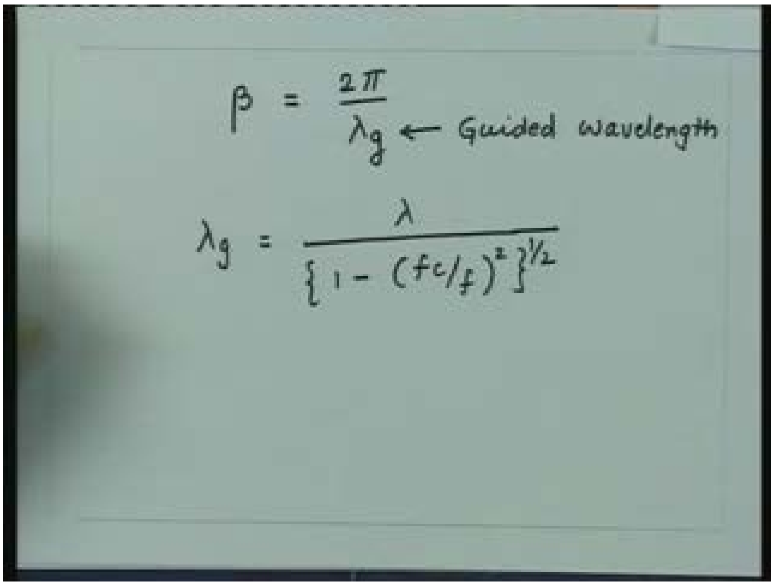

Once I do that then I can substitute for beta as 2 pi by lambda and that can be related to the intrinsic lambda as lambda g that will be equal to lambda divided by 1 minus f_c upon f whole square, square root. Few things now can be observed from here, this is the wavelength of wave in an unbound medium, this is the wavelength which we are going to measure inside this bound structure along the wave guide and for travelling wave the frequency has to be greater than the cut off frequency.

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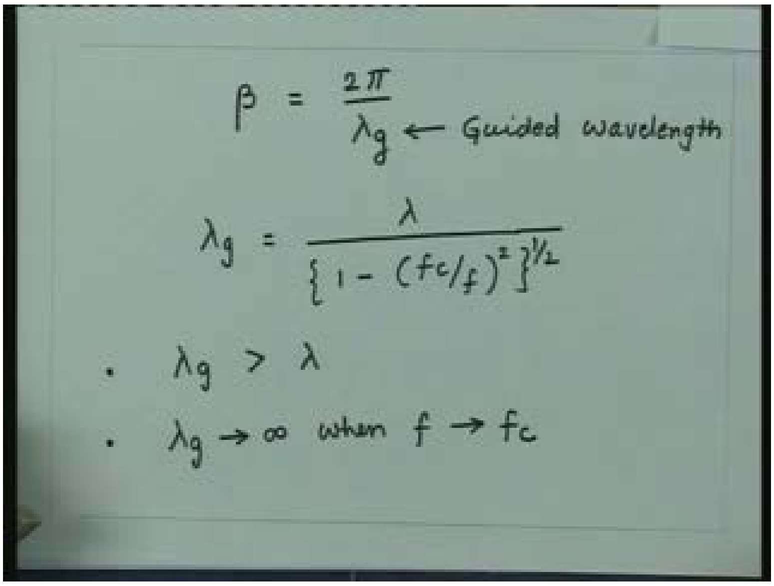

So, as the cut off frequency, the first thing we notice here that this quantity is always going to be less than 1 for a travelling wave and therefore the guided wavelength is always greater than the intrinsic wavelength in that medium. So, first thing we see is the guided wavelength is always greater than lambda intrinsic wavelength in a medium. As the frequency tends to infinity, this quantity will become 0 and that time this lambda g will approach lambda but this will never become equal to lambda because you will always have a frequency which is finite, so this quantity will be always a finite quantity and this quantity will be always less than 1.

So, we do not have for a guided structure, no matter what frequency we operate with, we will never have the guided wavelength equal to the intrinsic wavelength in that medium. Second thing what we note from here is that as the frequency approaches the cut off frequency, this quantity tends to 1 and wavelength becomes larger and larger and at cut off frequency the wavelength become infinite. So, second important conclusion we get is lambda g which is the guided wavelength, it tends to infinity when the frequency approaches the cut off frequency. Now knowing this value of beta, we have seen for parallel plane wave guide and same thing is true in this case also that omega by beta gives me the phase velocity and now the phase velocity will become function of this f c upon f so when f c upon f is much much smaller compared to 1 that time the phase velocity will approach the intrinsic velocity in the medium otherwise when the frequency approaches the cut off frequency again the phase velocity will become infinite.

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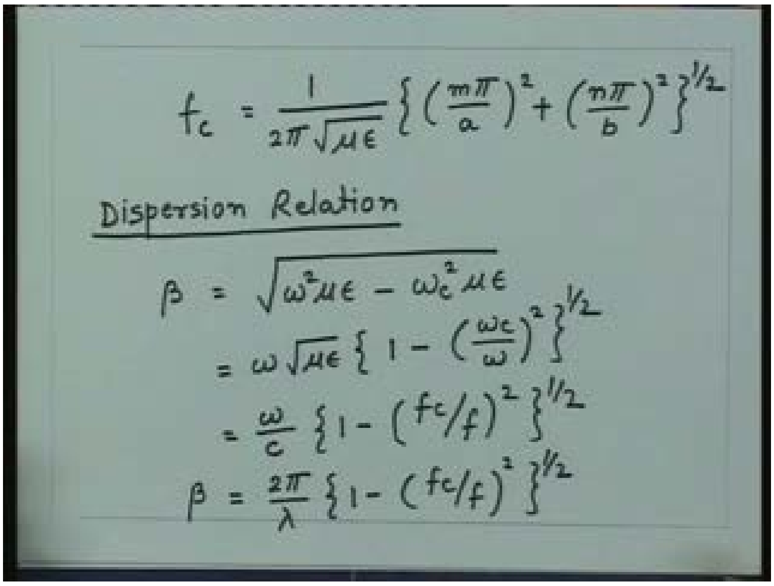

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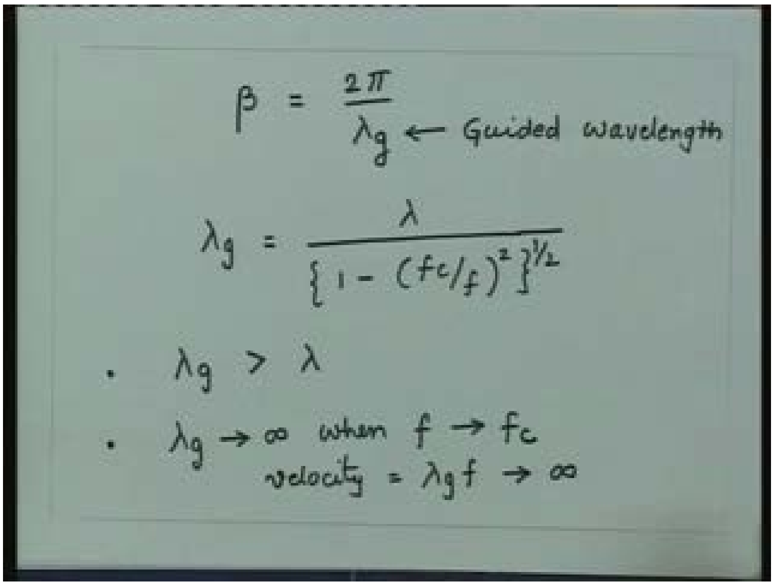

Same thing is happening here that the frequency multiplied by lambda g that gives me the effective velocity of wave on this structure. So, when frequency is much larger compared to f c, the velocity approaches the intrinsic velocity c and when frequency is approaching cut off frequency then the velocity tends to infinity. So, since in this case lambda g tends to infinity, the velocity of the wave which is lambda g into frequency that also would tend to infinity. So, these are certain important conclusions we can draw for this wave which are valid for all transverse electric as well as transverse magnetic case.

Now come back to the field expression again and try to now investigate the relative cut off frequencies for the different modes and we have seen now that there are three modes which we can call as the lowest order mode. One is TE 1 0 mode, TE 0 1 mode and TM 1 1 mode. So, we can take mode here TE 1 0, we can take TE 0 1 and we can take TM 1 1, these are the lowest indices are possible for the TE and TM modes.

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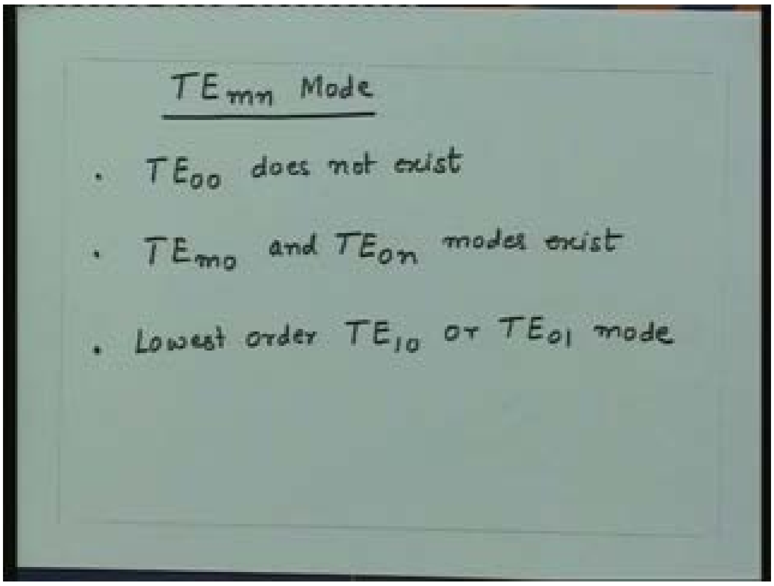

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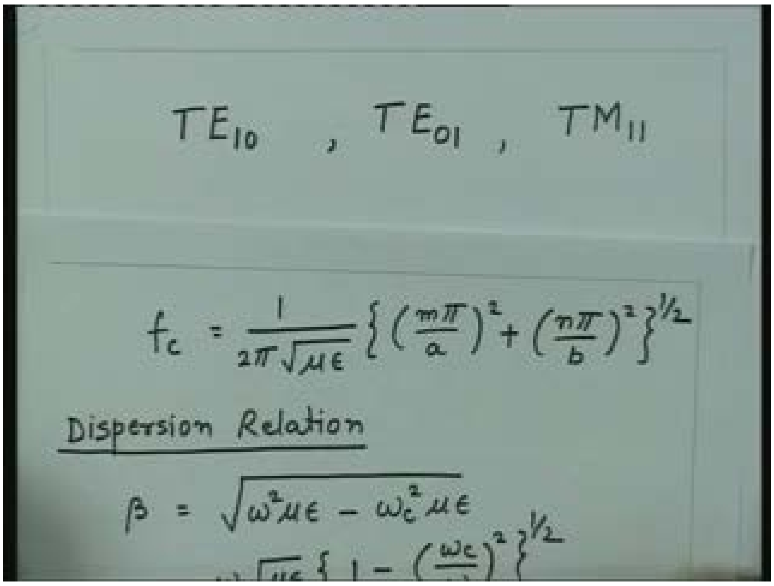

The cut off frequency for TE 1 0 mode would correspond to n 0 and m equal to 1, so the cut off frequency will be 1 upon 2 pi square root mu epsilon. So, if I write down cut off frequency for this, this will be f c TE 1 0 that will be equal to 1 upon 2 pi square root mu epsilon into pi upon a because n is 0, m is 1 into say pi upon a.

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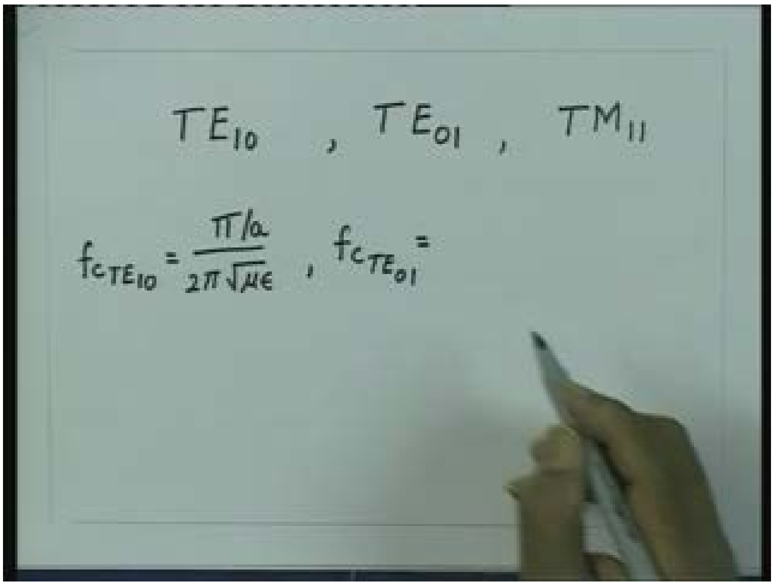

The cut off frequency for this mode TE 0 1 mode will be fc TE 0 1 that will be pi upon b divided by 2 pi square root epsilon.

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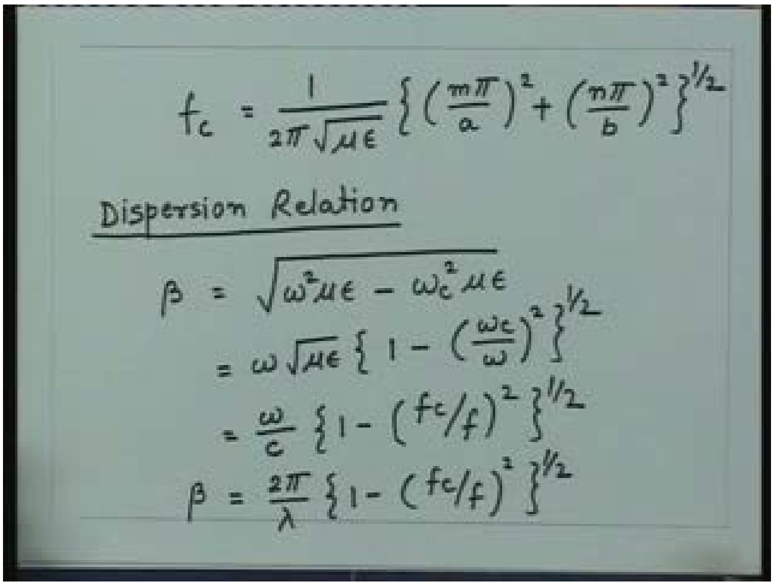

So, this will be pi upon b upon 2 pi square root mu epsilon and for TM 1 1 mode both of these m is 1, n is 1.

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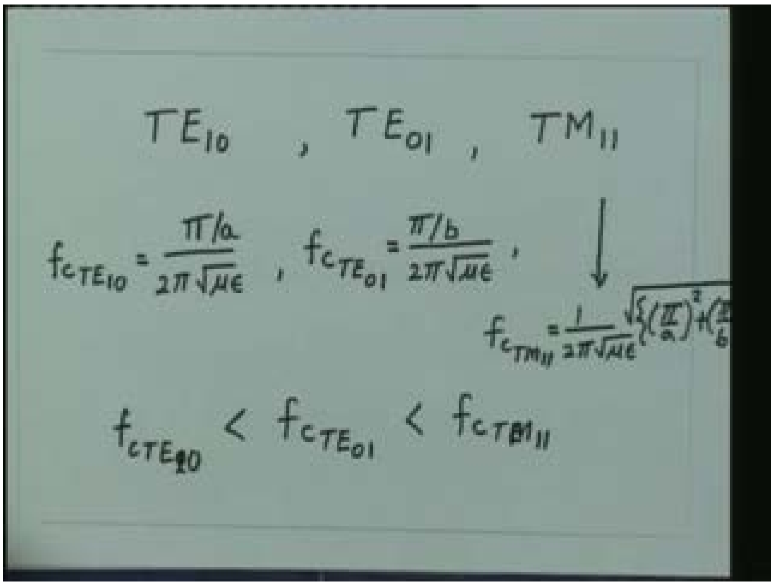

So, for this mode you will get the cut off frequency which will be fc TM 1 1 and the same cut off frequency will be for TE 1 1 also that will be equal to 1 upon 2 pi square root mu epsilon pi upon a whole square plus pi upon b whole square, square root.

Now, recall by definition we have a greater than b, so if we are not considering square wave guide where of course these two quantities will become equal otherwise for a rectangular wave guide since a is always greater than b, this frequency is smaller than this and this frequency will be smaller than this because you are having here now both the terms pi a and pi b. So, in general if I take these three modes, essentially I have got the cut off frequency fc TE 1 0 is less than the cut off frequency for TE 0 1 is less than for the cut off frequency TM 1 1. And we have seen the mode TE 0 0 or TM 0 0 do not exist that means this is the lowest frequency which can propagate on this structure that is the absolute minimum frequency which the structure will support.

So, whenever we try to excite a rectangular wave guide, the possibility of exciting this mode is the highest because if at all the energy is going to propagate, it will be propagating at least in this frequency. It is possible if the frequency lies between this and this, this will propagate but others will not propagate because they will be below cut off. If the frequency lies somewhere here then these two will propagate, this will not propagate and so on but this is the lowest frequency which the wave guide is capable of supporting. That is the reason this mode, the TE 1 0 mode is the important mode for rectangular wave guide and this mode therefore is differed to as the dominant mode of the rectangular wave guide, so we introduce this word what is called the dominant mode and this mode essentially means TE 1 0 mode.

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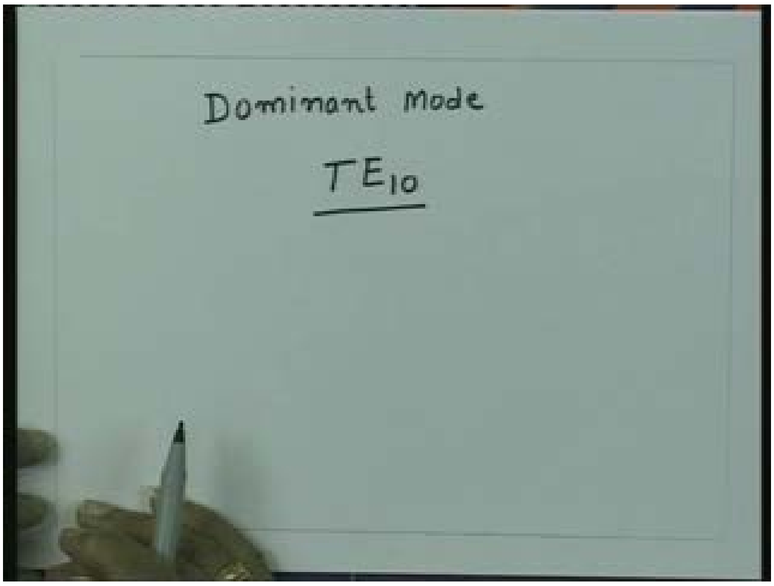

So, this one has now the first index one that means this has the half cycle variation, fields have half cycle variation in the x direction and the field is constant in the y direction, that is the mode which is going to propagate inside this structure. And since this is the important mode because if at all energy propagates is going to propagate in this mode, we can have a little more detailed analysis of this mode rather than talking about the general mode of TE mn or TM mn.

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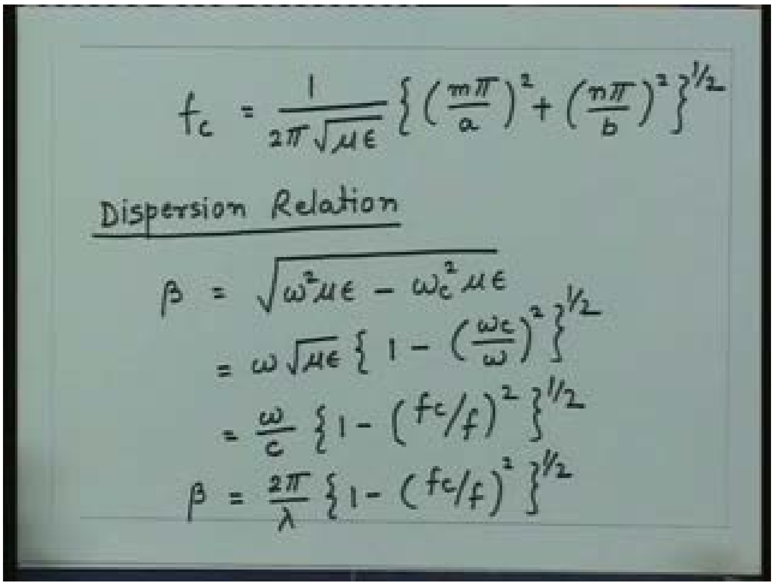

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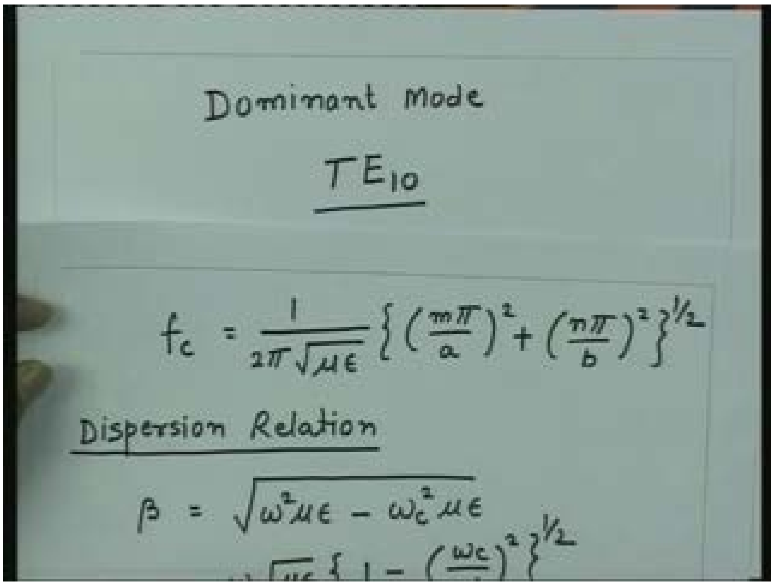

One thing may also note that since the cut off frequency expression is this depending upon the value of a and b, it is possible that the TE 0 1 mode may have a frequency which is lower than or higher than the TE 2 0 mode. I can have the frequency which is TE 3 0 mode, so that TE 3 0 mode could be lower than the TM 1 1 mode or TE 1 1 mode. So, depending upon the dimension, the ratio of a and b it is possible that the higher order TE modes like TE 2 0 or 3 0 they may have cut off frequency smaller than TM 1 1 or they may have a frequency more than that. So, one cannot make any general statement about what is the order of the cut off frequencies for the various modes of TE m n or TM mn.

However, one thing is absolutely clear that the lowest frequency is always TE 1 0 mode, beyond this I cannot tell what the cut off frequencies would be, what will be the order of cut off frequencies but this is the frequency which is always going to be lowest. That is the reason if we wanted to have the single mode operation inside a wave guide and we will see later why single mode operation is desirable inside the wave guide, the energy will always propagate inside this dominant mode which is TE 1 0 mode. So, that's why we now make little detailed investigation about the TE 1 0 mode. So, first thing we can now write down the fields for TE 1 0 mode, so essentially we get the field expression for the H z, substitute now m equal 1, n equal to 0 in this.

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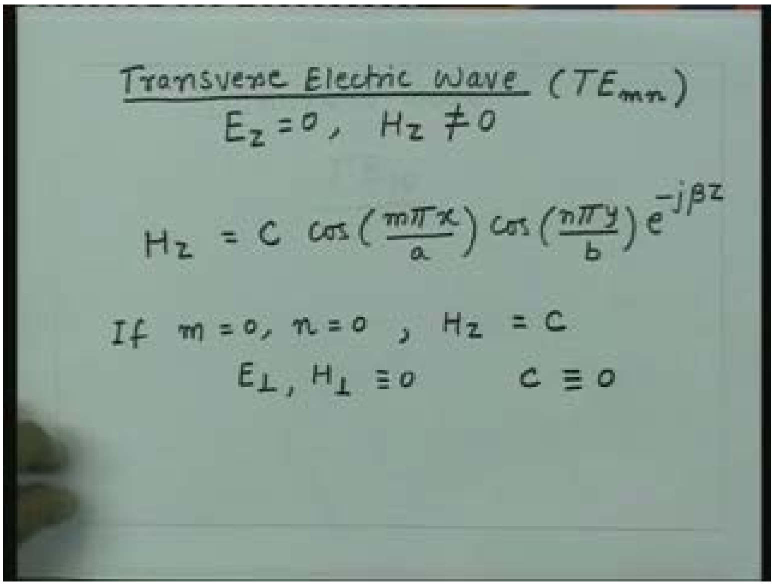

So, we get H_z for TE 1 0 and then substituting in the transverse field expressions, we can get the remaining components for the TE 1 0 mode.

So, for this case the H z now is equal to the constant times cos of m equal to 1.

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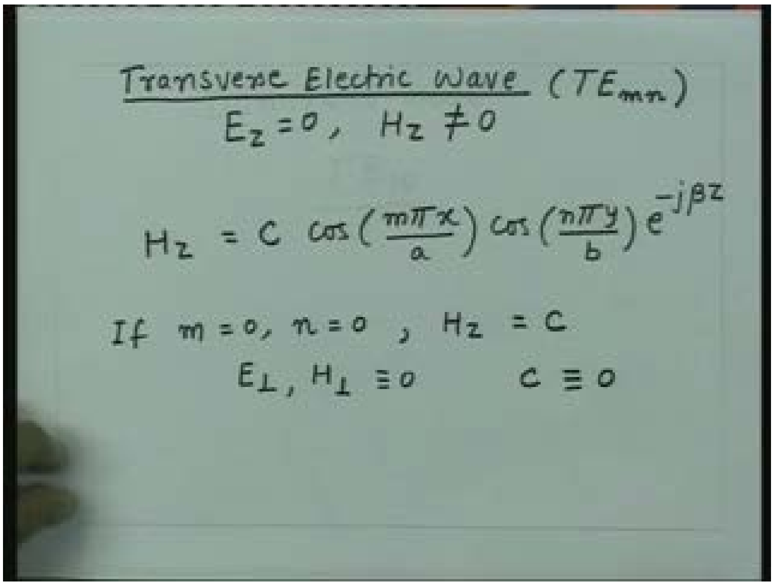

So, you substitute m equal to 1 here, it will be pi upon a into x, this quantity is 0, so this is 1.

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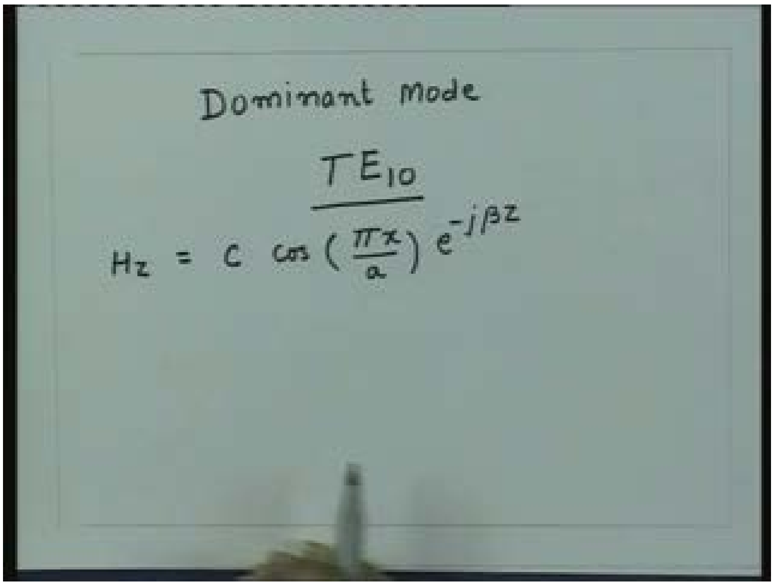

So, this will be pi x by a e to the power minus j beta z.

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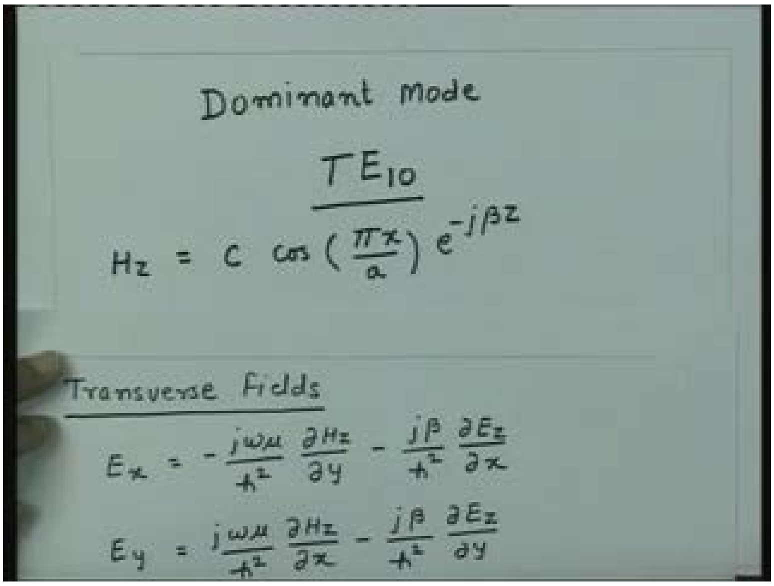

First of all note here that H z is only a function of x that means the derivative of H z with respect to y is 0. So, I have here the component E z is already 0 for TE case, so this thing is not there. We are having here for E x, the derivative of H z with respect to y and this is not a function of y, so this quantity is 0 that’s why E x is 0 for this mode. So, we get the E x is equal to 0 for this mode.

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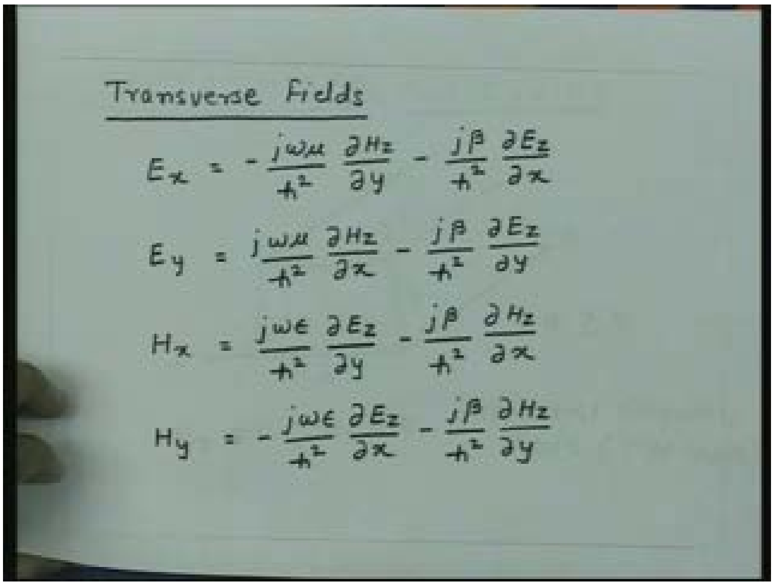

Similarly, we can see again H z has a y derivative, derivative with respect to y that is for H y, so this quantity also will be 0. So, for this mode the H y will also be 0.

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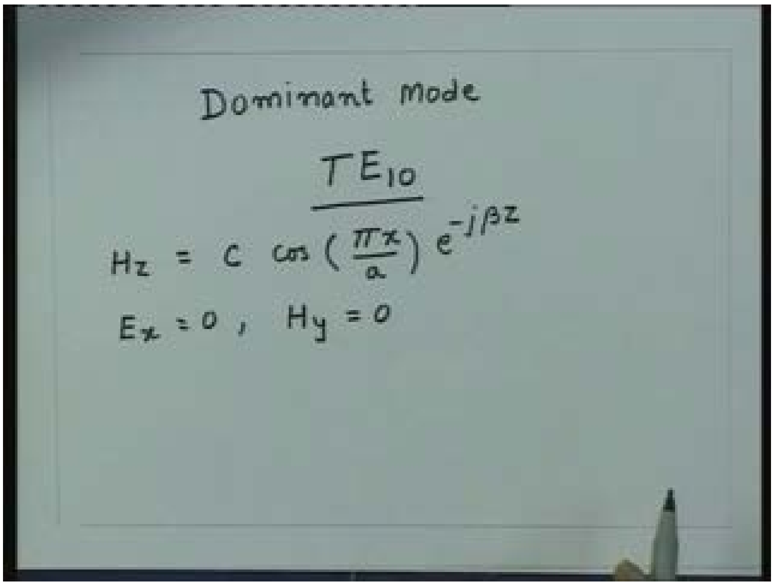

So, the quantities which we'll have now for this field is the field which is E y. Now, H in this case since you have taken m equal to 1 and n equal to 0, the H which we have got which is this m pi upon a whole square plus n pi upon b whole square, n is 0, m is 1, so h is pi upon a.

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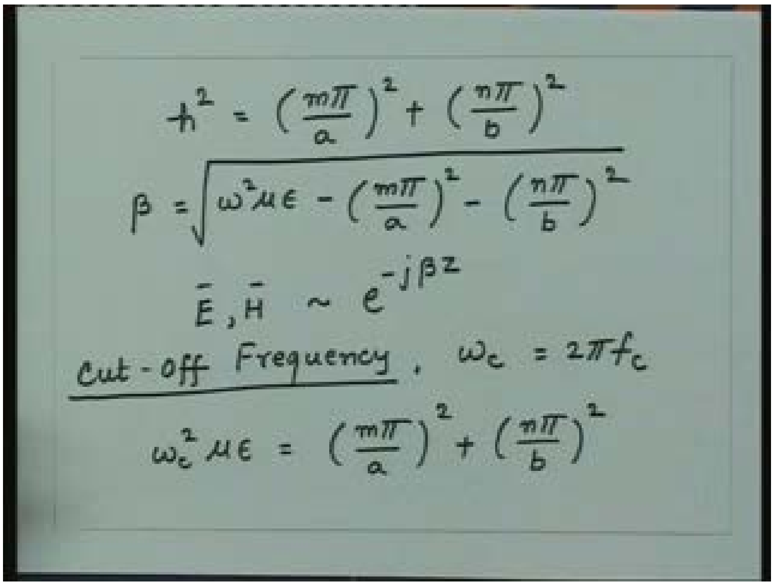

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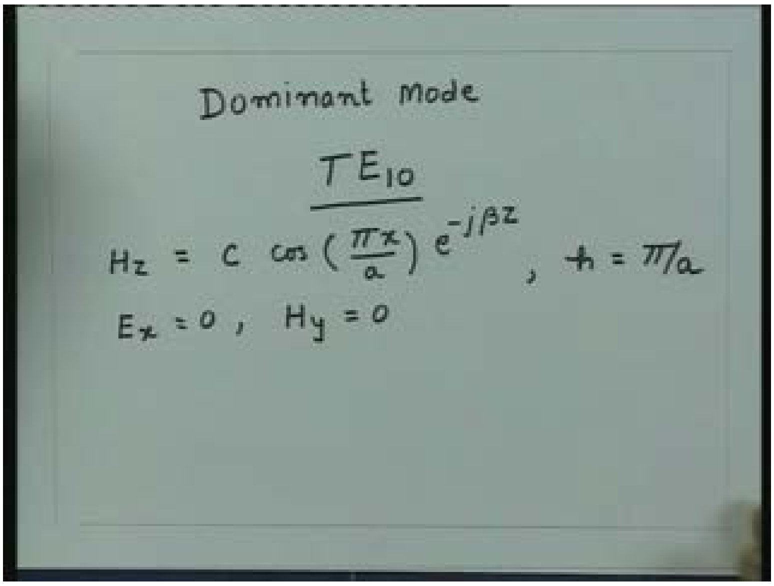

So, for this we have h is equal to pi upon a, so I can now substitute into this and I can get the E y component which is j omega mu upon h square which is pi upon a whole square, so that is j omega mu upon pi upon a whole square.

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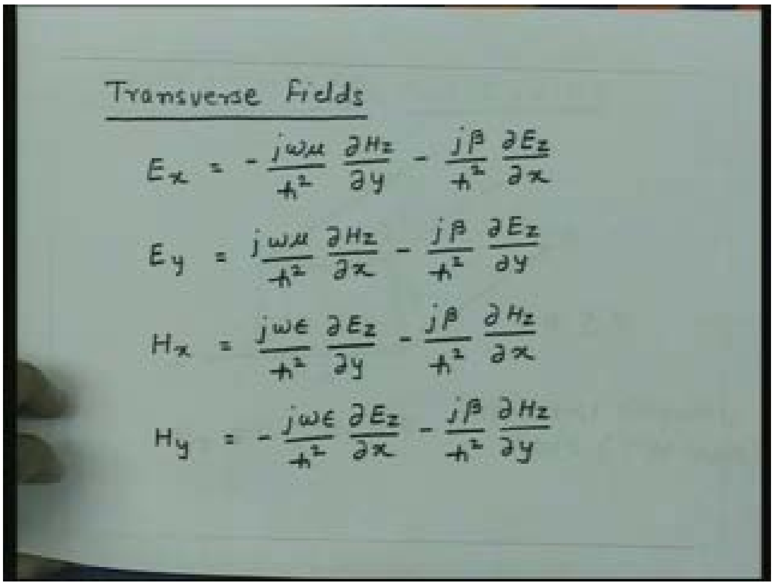

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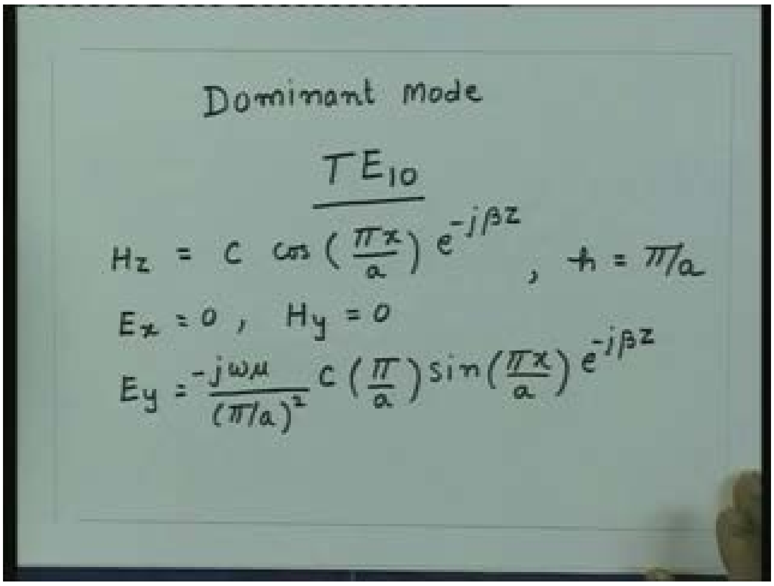

d Hz by dx, so if take this, this will give me c minus sign pi upon a sin of pi x by a e to the power minus j beta z and I will get a component which is H x, H y is 0. So, H x component will be equal to j omega epsilon upon pi upon a whole square, this quantity with a minus c pi upon a sin of pi x by a e to the power minus j beta z. I can simplify and get the field expression now explicitly for the TE 1 0 mode. So, TE 1 0 mode has only one electric field component and that is y and two magnetic field components H x and H z.

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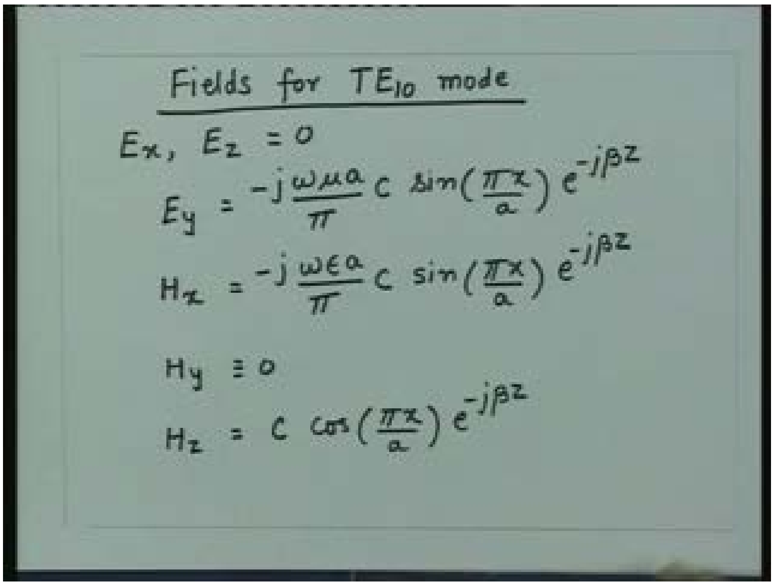

So, now we have the fields for TE 1 0 mode, so we get E x E z equal to 0. E y equal to, I can just simplify this 1 pi upon a will cancel, so this will be minus j omega mu a upon pi into c sin pi x by a e to the power minus j beta z. H x will be equal to minus j omega epsilon a upon pi c sin pi x by a e to the power minus j beta z. H y is 0 and H z is equal to c cos pi x by a e to the power minus j beta z. So, these are now explicitly the field for the dominant mode of a rectangular wave guide and normally we operate this wave guide in this mode TE 1 0 mode because as I mentioned many times we have a requirement that there should be single mode propagation on this wave guide and that single mode propagation will take place in this mode which is dominant mode.

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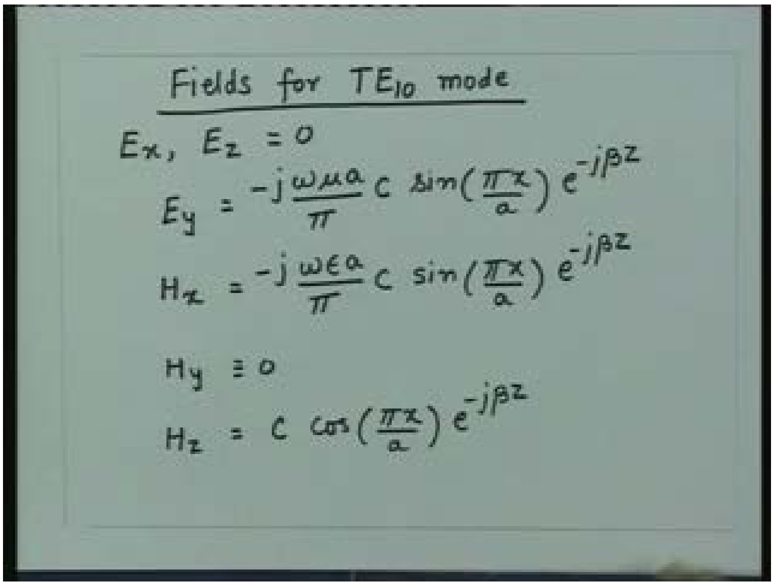

So, these are the fields which are essentially going to exist on this wave guide. The cut off frequency as we talked about and the cut off wavelength which we talked about, we can calculate now the cut off wavelength for this lowest shorter mode or the dominant mode. I can go back and substitute into the expression for the wavelength and get the cut off wavelength from here and I can calculate the phase constant and the guided wavelength of this field on the wave guiding structure.

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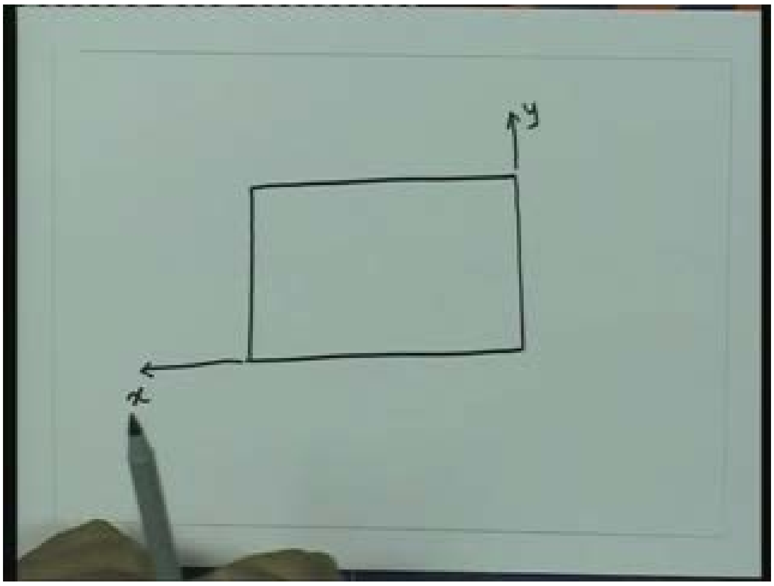

So, physically now if I look at how the fields are firstly the rectangular wave guide cross section, if I draw like that the electric field is having only y component and this is the y direction, this is x direction and z direction is going inside the plane of the paper, electric field is y oriented which is this and it is having one half cycle variation, so it is maximum here, zero here, zero here that's what the sine function is telling. So, a field here which is maximum at a by 2, x equal to a by 2, at x equal 0 and x equal a this field go to 0, so the E y will be 0 here, it will be maximum here, it will be zero here.

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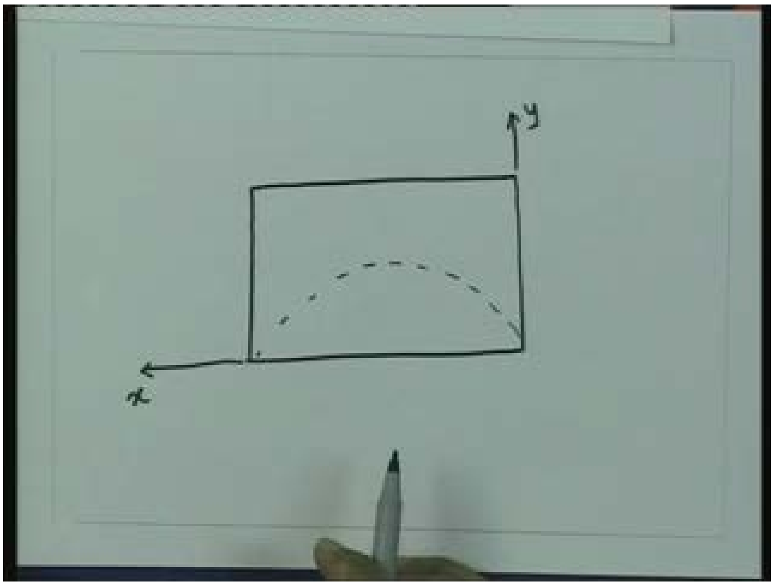

So, if I draw that variation, this variation will be one half cycle variation in this direction for E_y and there is no variation for this field in the y direction.

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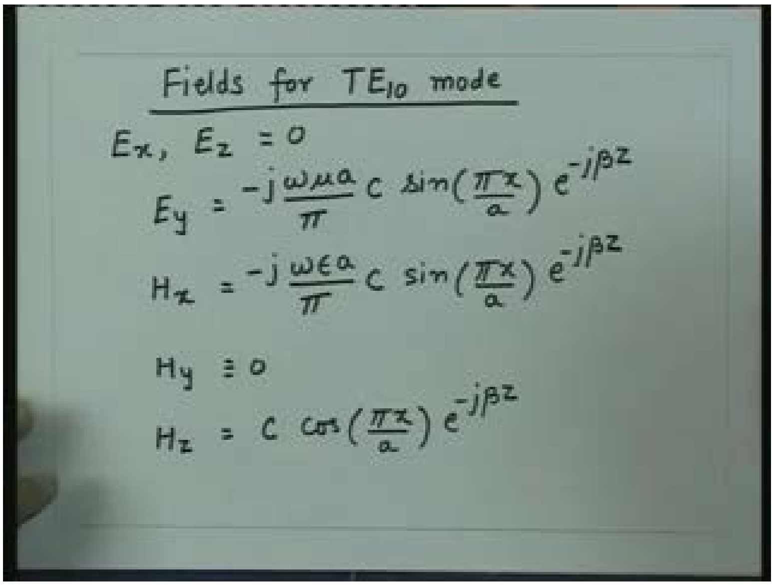

So, the field varies in x direction by half cycle and no variation in y direction.

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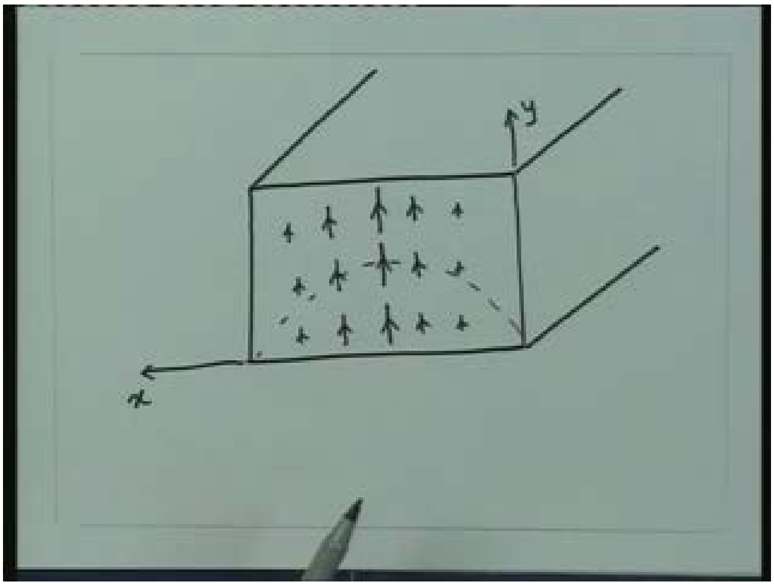

So, if I want to represent this field now in terms of the vectors or the arrows then here the arrows are large but the field is very large here and in this direction the field is constant, so they have same size of vectors. If I go now in this direction the field decreases, so here I will get like that, like that. If I go still further I will get like that and if I come here, it will become zero.

Same thing is going to be on this side. So, here I'll get the field which will be like this, go further and when I go to the wall it will become 0. So, if take now the electric field and if I measure it here, we will get the maximum electric field at the center of this wave guide, direction will remain like this and the field strength everywhere on this line will be same. Similarly, if I move here it will be same, only thing this will be smaller compared to this and if I move now towards the walls this component which is tangential component to these walls will go to zero. So, this field will become zero here, this will become zero here. We can now visualize this field and we will see little later, a little more visualization of these fields in a different wave guiding structure but at this moment it appears that this field is maximum at the broader wall of the wave guide.

So, if I take this structure wave guide like this then this field is going to be maximum here at this broader wall of the wave guide. Same thing essentially will happen to the other modes also, if I take the higher order modes again you will find the locations where the electric field and magnetic fields will be maximum. Why this information is important is that one may ask a question that once the wave guide is given to you, how would this particular mode get excited inside the wave guide. Do I have a mechanism by which a particular mode can be excited or will the wave guide simply decide the excitation of the modes?

Can we selectively excite certain mode inside a wave guide? And by looking at the field distribution essentially that becomes clear that yes if you create a mechanism by which the field will be maximum at this place then that excitation mechanism will support this field which is maximum here and then the mode which will get excited inside the wave guide will be TE 1 0 mode provided the size of the wave guide is such that the TE 1 0 mode propagates on the wave guide. So, the two things are required, firstly the size of the wave guide should be large enough so that the frequency is greater than the cut off frequency for that mode. Secondly, the excitation mechanism should be such that the field or the mode which you want to get excited, those field match with the excitation.

So, if I take a field distribution for which the field was zero at some location and if I try to put the excitation there, obviously the mode will not get excited because the field for that mode is zero at that location. So, even if you provide excitation at that point, there is no excitation of the field inside the wave guide because at that location this mode has an amplitude zero. So, for excitation of TE 1 0 mode, normally what we do, we put some kind of a probe here which goes inside the wave guide on the broader wall at the middle of that and because of that you have the fringing fields.

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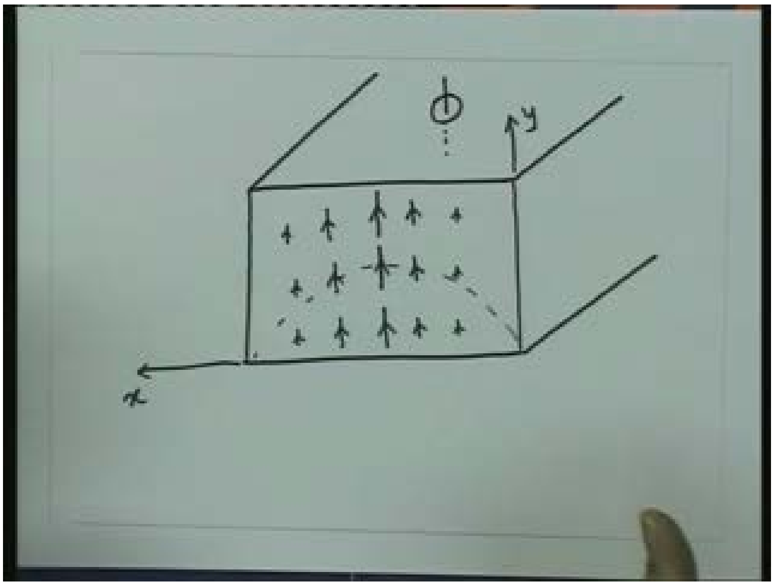

Now the mode which we talked about these are the field distributions which satisfy the boundary conditions. Now, here we are exciting the field which is a sudden change of electric field at that point then one can show that to satisfy the boundary conditions here for the field, you require all possible modes of the wave guide whether they are travelling or decaying because these are essentially telling you the orthogonal functions which satisfy the boundary condition inside the structure. So, locally around this probe all kinds of modes will get excited inside this wave guide including the field which are decaying field, only as we travel further in the wave guide those fields which are below cut off they will be dying down rapidly, only that frequency for which the cut off frequency is less than the frequency of this will travel. And if we make sure that that frequency is larger than the cut off frequency of the T E 1 0 mode but smaller than any other cut off frequencies, you get a guaranteed mode of TE 1 0 inside the wave guiding structure. So, essentially a TE 1 0 mode inside a wave guide can be excited by putting a probe which can excite electric field inside the wave guide at the middle of the broader wall.

So, in practice whenever we do the experiment or we carry the high frequency signals like microwave signals, these signals are carried by a rectangular wave guide and this rectangular wave guide always operates in a mode which is the dominant mode which is TE 1 0 mode. One can now ask a question I have been repeatedly saying that we should operate this wave guide in the single mode operation, there are many applications where we want single mode operation. Question, one can ask is why do we want single mode operation and the answer essentially lies in our dispersion relation, so we go back to our dispersion relation which says now the phase constant is a function of m and n and since the phase constant is the function of m and n, the velocity of this mode will also be the function of m and n.

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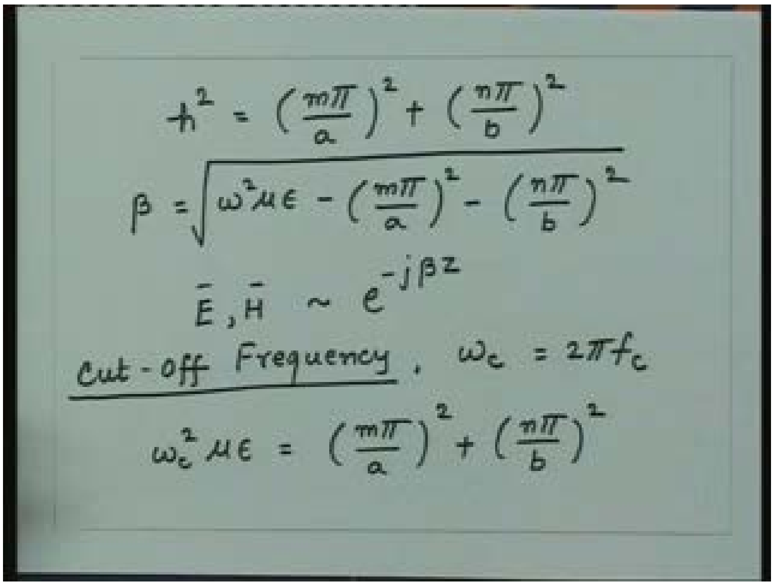

What that means is that for a given frequency omega, the different modes are going to travel with different speeds. Now if you want to send the information on this wave guide then we'll try to put the energy inside this wave guiding structure and then if large number of modes can be supported by the wave guide, if the wave guide doesn't have the single mode operation, the energy will get distributed into various modes that means various combinations of m and n. Each mode will have its own velocity for travelling, so as they travel the energy which is going on different modes essentially separate out, the phase relationship between different modes is broken.

Now imagine a situation that we transmit a signal which is not sine wave sinusoidal signal, we transmit a pulse that have frequency. Now, if the energy is divided into different modes and different mode travel with different speed, when the energy reaches on the other side, other end of the wave guide all mode energy will not reach at the same time that means the energy packet which we send will not appear like a packet, it will be distributed in time because some mode will arrive earlier, some mode will arrive later so that dispersion phenomena which we talked about essentially will give me the broadening of the signal in time as it travels on the wave guide. And this is happening because energy is getting distributed into various modes and various mode travels with different speed.

To avoid this we try to put the energy only into one mode, so that the energy remains in that mode and then the distribution of the energy or differential delays which comes because of the multiple mode propagation inside the wave guide is avoided and we do not have broadening of the signal when it travels on the wave guide because of the multi-mode propagation. This is the aspect which essentially one has to make use of when we design the wave guides at high frequencies.

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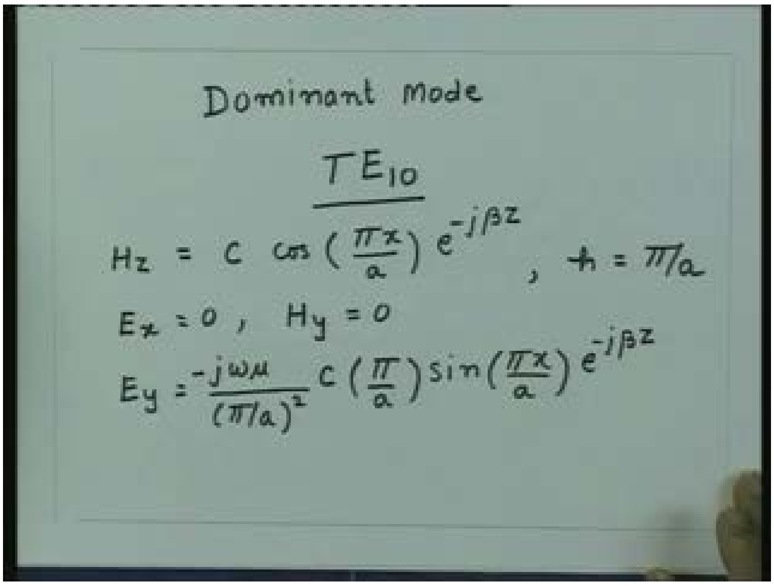

So, just to conclude for a rectangular wave guide the important mode is the transverse electric mode T E 1 0 mode that mode we also call dominant mode because it has lowest cut off frequency and for this frequency if we make sure single mode propagation takes place over certain range of frequencies. So, when experiment we make sure the frequency lies in that range, so there is single mode propagation.