Microwave Integrated Circuits

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Module 1

Lecture No 01

Introduction, Transmission lime equations.

Hello, welcome to the 1st module of this course, microwave integrated circuits. I'm your instructor, Prof Jayanta Mukherjee of Electrical engineering Dept of IIT Bombay. So in this course, we will be discussing primarily microwave engineering. As you know, microwave engineering is a field in Electrical engineering where we deal with signals having a certain frequency range. This frequency range is usually between 1 GHz to 30 GHz. Although, both lower than this frequency and above lower than 1 GHz and above 30 GHz also, the principles that we study in this course can be applied but usually this is taken as the boundary of the microwave engineering.

Now the key aspect of microwave engineering is the wavelength of the signal. When we have signals between 1 GHz and 30 GHz, the wavelength is in centimetre if we consider propagation through vacuum. For signals which are about 30 GHz, there the wavelength becomes in millimetre. And again for very low frequency signals, the wavelength goes in metres. So microwave engineering is more or less this is how we can classify that those range of frequencies for which wavelength remains in centimetre.

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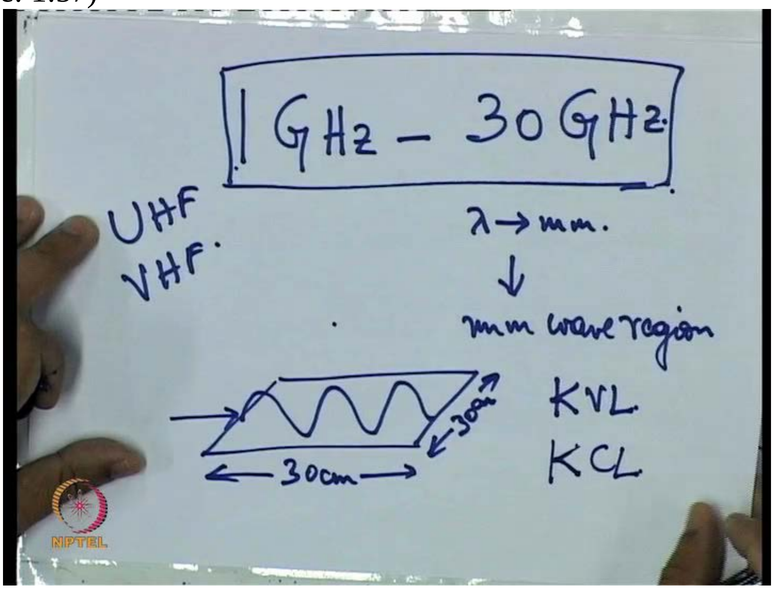

Microwave engineering basically involves signals which lie between 1 GHz to 30 GHz. Now beyond 30 GHz, the wavelength is in millimetre. That is why it is called as a millimetre wave range region. And below 1 GHz, we have the UHF and VHF ranges. So this is more or less the range for which microwave engineering is defined. Now what is so special about this range of frequencies? If we can take it with a simple example. Consider a single copperplate where a signal is applied and say the voltage or current wave that is formed on this plate varies in this fashion.

Now what happens is suppose this is let is say the width and length of this plate is 30 cm by 30 cm. And we know that from normal KVL, Kirchoff's voltage low, at low frequencies or DC if a signal is applied, then the entire copperplate as long as it is a good conductor, entire copperplate will have the same voltage but that is not the case here because here the wavelength of the signal is comparable to the dimensions of the plate. That is why, each point has a different voltage depending on the wave structure. So that is one point.

So the traditional KCl and KCL that we often use for solving network problems at low frequency or DC are no longer applicable when we come to the microwave range of signals. Now because there is wave being transported, at these frequencies, we will have to deal with the wave nature of signals.

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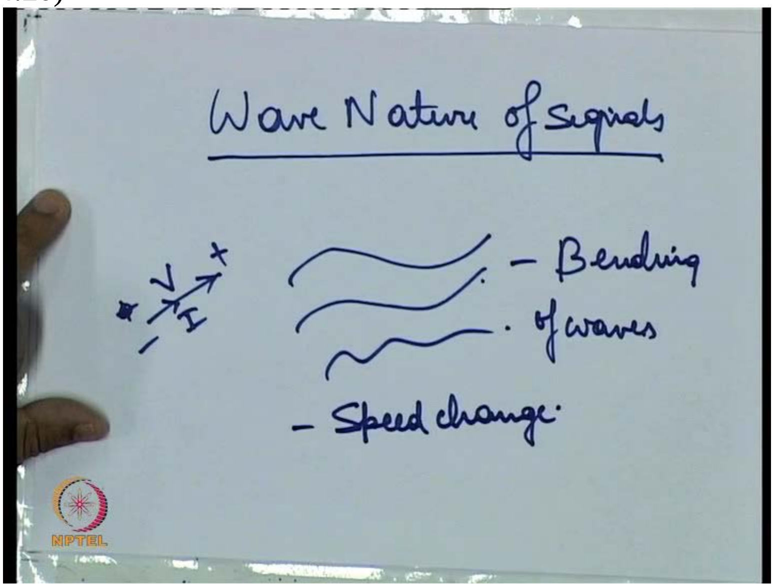

So the transmission can take place both along a conductor using the normal voltage-current relationships that we know. V-I, if there is a voltage, there should be a current like that.

Or, it can also the power transmission can take place through wave propagation. So when we have wave propagation, then we have to come across bending. So that is one effect. Then, there is a speed change. That is when a wave travels from one media to another, there is a change in the velocity of the wave. And this causes this in turn is one of the aspects of the wave nature of the signal. So these are some of the effects.

And the other as I said, since propagation need not always have a current and voltage relationship, so we can also have propagation through single conductor waveguides.

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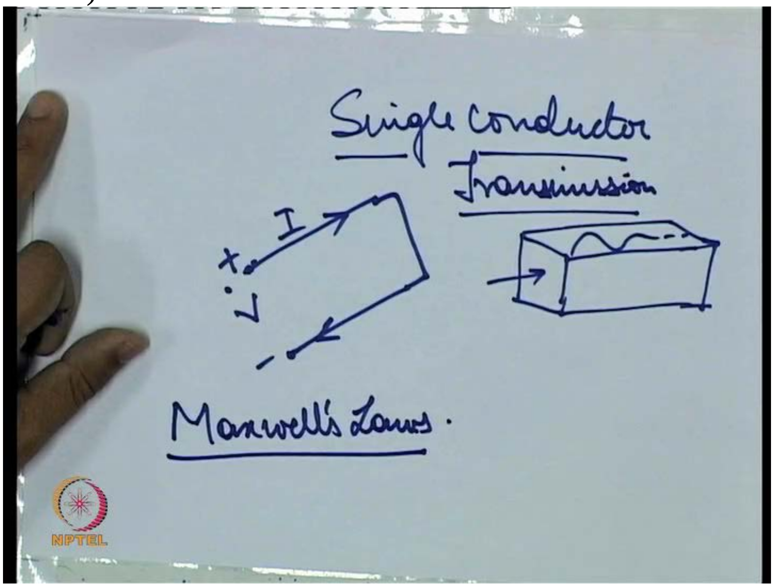

What I mean is, we know the traditional knowledge of Electrical Power transmission is that there has to be a certain voltage difference between 2 points and power is transmitted let is say between this point and this point by means of current and voltage. But as I said in microwave frequency that need not be the case. So it can be a simple wave based transmission. And since wave based transmission is happening, we need not have 2 conductors or current and voltage present.

It can be say, we have their dress a certain conductor called a rectangular waveguide where if power is incident, microwave power is incident then the wave travels through this waveguide. There is no special, there is no need of a special 2nd conductor. So that is another aspect of microwave power transmission that it can happen, the power transmission can happen using a single conductor. A single conductor transmission. So then, if KCL and KVL are not totally applicable for microwave engineering then what is applicable?

So the rigourous way of solving this is using Maxwell's laws. I am not going to go into detail about Maxwell's laws. You can find it in any electromagnetic textbook but what we will cover is the solutions of these Maxwell's laws. So the solutions of the Maxwell's laws…

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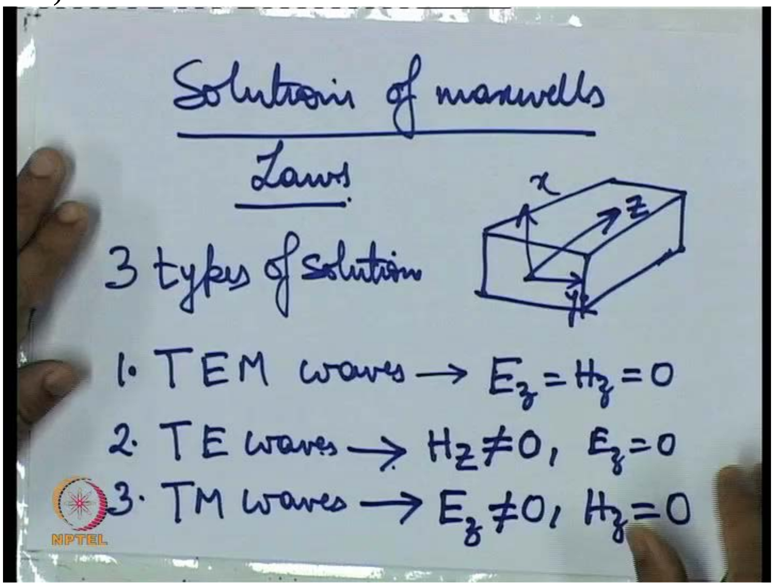

So this is the fundamental principle behind solving all microwave engineering problems that since KCL and KVL are not applicable, we can directly apply Maxwell's laws to every instance. And by applying Maxwell's laws to a particular waveguide what we call a rectangular waveguide like this, we get 3 types of solutions. 1st one is called TEM waves. 2nd is called TE waves and 3rd is called TM waves. TEM waves are waves which do not have any component of electric or magnetic field along the direction of propagation. Suppose our direction of propagation is along the +Z direction and X and Y are the other coordinate axis, then in TEM waves, we have EZ equal to HZ equal to 0.

In TE waves which are also known as transverse electric waves, we have no component of the magnetic field along sorry we have no component of the electric field along the direction of propagation but the component of magnetic field along the direction of propagation will be nonzero.And TM waves are the converse. That is, there will be no component of magnetic field along the direction of propagation but the electric field along the direction of propagation will have to be nonzero. Now what are the significances of these 3 types of waves?

Now, TEM waves 1st thing we have to note about TEM waves is that they are applicable only for 2 conductor waveguides.

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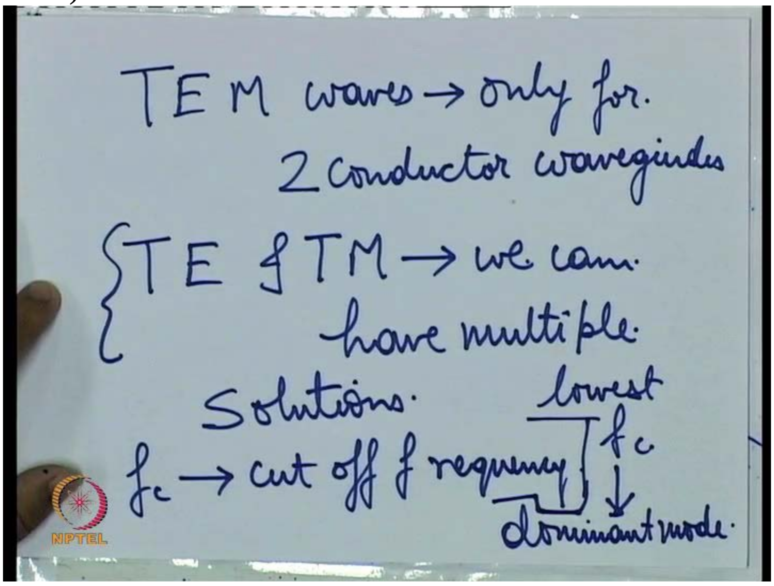

Only for 2 conductor waveguides. And there is a single solution for TEM waves. That is we cannot have there is a single TEM wave that can propagate through a medium. For TE and TM, we can have multiple solutions. Multiple solutions means, there can be more than one TE or TM wave passing through the same medium. The other property characteristics of TE or TM wave is they have something called as cut-off frequency.Cut-off frequency means a frequency below which a TE or TM when cannot transmit and the mode or that solution of the TE or TM wave which has the lowest cut-off frequency that is known as the dominant mode.

That is the definition. The mode that has the lowest cut-off frequency is called the dominant mode. These are kind of the fundamentals of how we can go ahead to understand the operation of various microwave devices these are the fundamentals that we have to know. Now coming back to this line.

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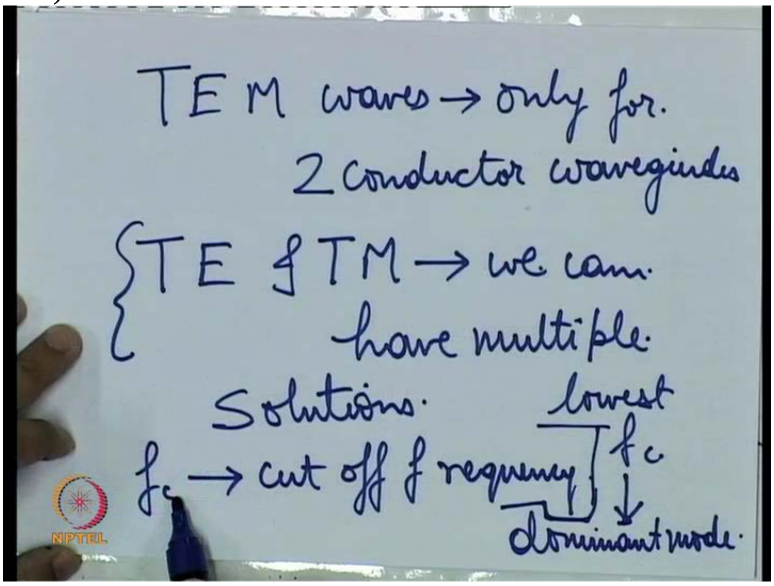

So FC is the cut-off frequency. Now let us take an example. Say we have what we call a cylindrical waveguide. So let us 1st start with what we call as a parallel plate waveguide.

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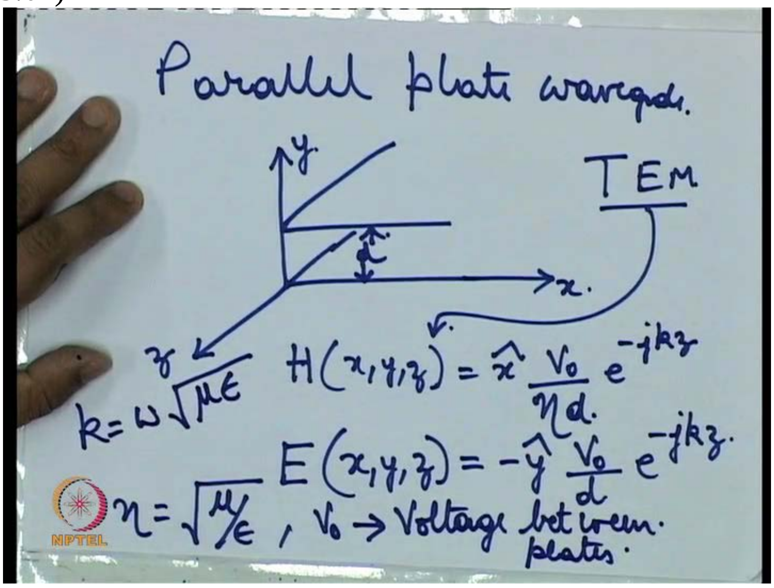

No parallel plate waveguide is a waveguide where we have 2 layers of metals infinite layers of metals separated by a distance, d. Now the electric and magnetic field solutions for this parallel plate waveguide are given like this. For the TEM mode, these are my solutions. This is of course obtained by Maxwell's equations where Eeta is the intrinsic impedance and Vo is the voltage between the plates. And K, the propagation constant is given like this. The TM solutions are given as so if we again apply the Maxwell's laws to find the TM wave solution they are given like this.

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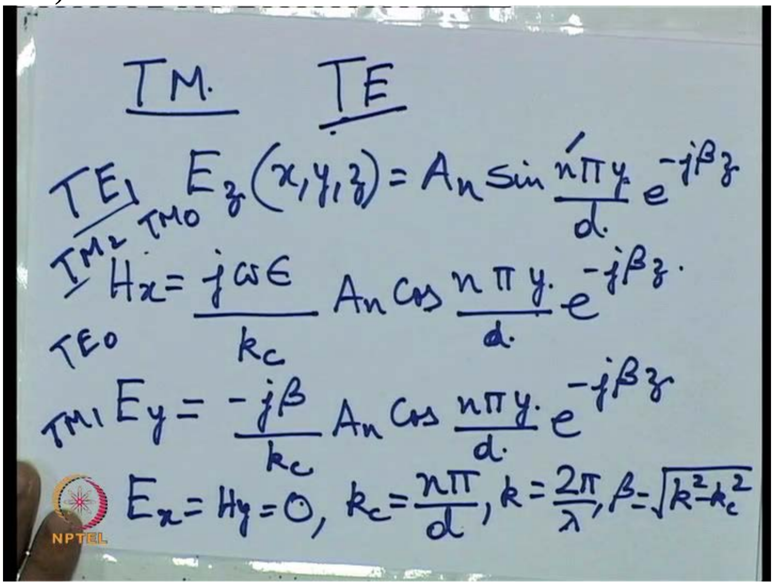

So this is the solution for the TM wave. Now as we can see, because of this constant n that appears inside this sinusoidal term what happens is that there are many solutions of EZ. For various values of n, we can have various solutions of EZ. And now the mode that has the lowest cut-off frequency will have the, will be called the dominant mode. So we will have for a parallel plate waveguide we will have modes like TE1, TM 2, TM0, TE0, TM1 and so on. These are the various modes, T1, TM 2, TM0, TE0, TM1 depending on what the solution for whether you are taking TM or TE solution and the value of n.

So in the same way that we had these solutions for the TM mode, we will also have a solution for the TE mode. Now, if we as I said, there is a certain cut-off frequency for each waveguide, and if we draw a relationship between this beta and omega.

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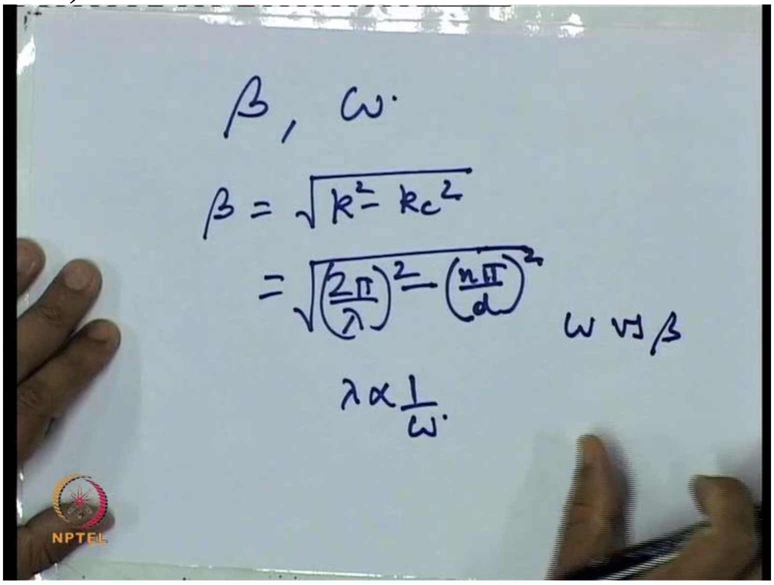

So even for a parallel plate waveguide, we saw that beta is equal to K square - KC square and then K is given as 2pi upon lambda whole square - KC is given by npi upon d. And we know that 2pi upon lambda is inversely proportional to omega.

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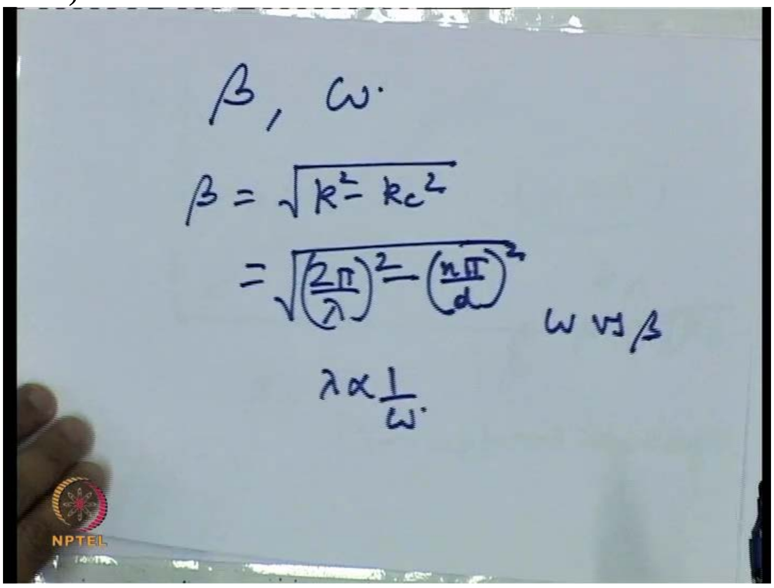

So using this relationship, if we plot a curve between omega vs beta, what we get is something like this. Now this is the line for when omega is directly proportional to beta as in the case of TEM wave.

For TEM wave, we saw K or beta is equal to omega times square root of myu epsilon. Then for TEM wave, the relationship between beta and omega is a straight line. But for this TE and TM wave, TM modes, we saw that the relationship is given by this kind of a line. Now this what is this beta? Beta we saw is a kind of, you can define it as 2 pi upon lambda G where lambda G is the apparent wavelength. So while lambda is the actual input of wavelength, wavelength of the input signal, lambda G is the apparent wavelength inside the media or the device. Now this kind of curve as from this relationship that is showed just now between beta and omega, beta and lambda since lambda is proportional to omega, we can write this equation.

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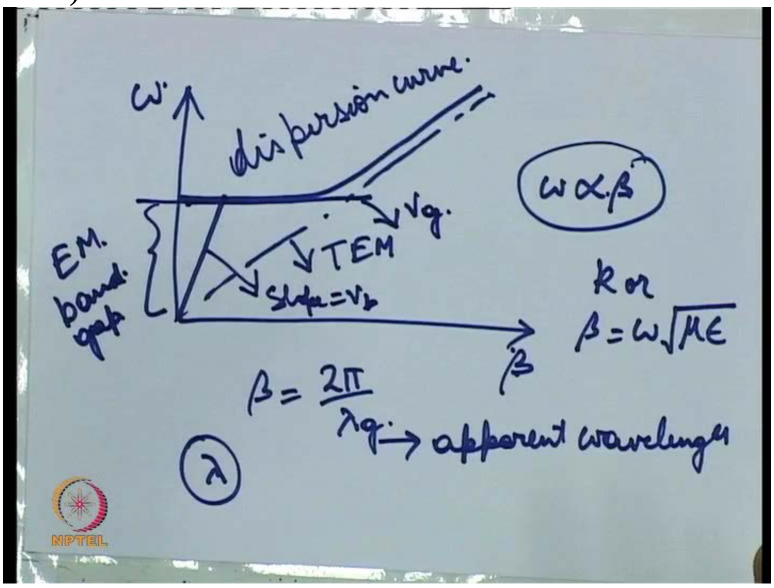

So this curve that we obtained is called as a dispersion curve.It is called as a dispersion curve because of this curve was a straight line like this, there would have been no dispersion. That is, all frequencies would have been travelling at the same velocity. But because of this bend present in the curve, 1st of all we know that there are certain frequencies which are forbidden. So this is called the electromagnetic bandgap which are the forbidden frequencies and the phase velocity or the velocity with which a phase, a constant phase of the wave goes, is equal to the caudal slope that is the slope of the line joining any point to the origin. So the slope of that line is the phase velocity and the tangential velocity, slope of the tangent to any point gives what you call as group velocity.

Now group velocity can be considered as a velocity of depletion envelope or if you have an amplitude modulated signal, then the velocity with which the entire envelope of the amplitude modulated signal travels that is called as the group velocity. Whereas phase velocity is the apparent velocity with which the constant phase of a single frequency travels. So coming back to our curve here, if the group velocity is constant, then there will be no distortion or dispersion between frequencies. Because the group velocity is not constant and keeps changing as you go along this curve, there is dispersion or distortion present in the signal. Hence the name, dispersion diagram.

So these are some of the fundamentals as far as the various types of solutions and types of modes that are present in microwave devices. Let us go to a circuit perspective.

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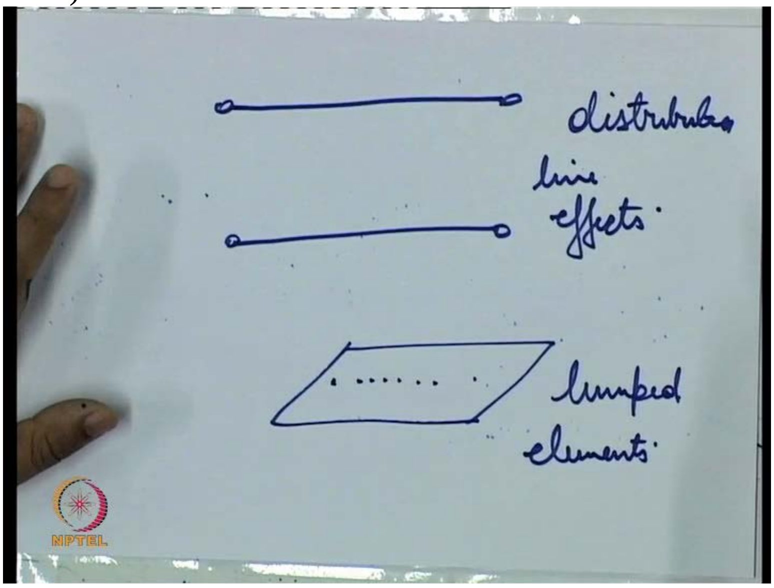

Now, what happens is when I said that whenever a wavelength of a signal is comparable to the dimensions surface the circuit, you have this microwave distributed lines what you call as distributed line effect. What that means is, you cannot consider that line or say if we go back to our rectangle plate, you can no longer consider this plate as a single conductor or a lumped element. We have been familiarised with lumped elements at low frequencies where the wavelength is much larger as compared to the dimensions of the circuit but when the dimension of the circuit is comparable to the wavelength of the signal, we can no longer approximate everything with lumped element. We have to consider the impedance at each point as the wave travels.

So that is why, this distributed line effects are a prominent feature of microwave engineering and that happens because of this low wavelength. So, 2 major things about microwave engineering. One is the wave nature for which we have already obtained the solution and the 2nd is the distributed effects.

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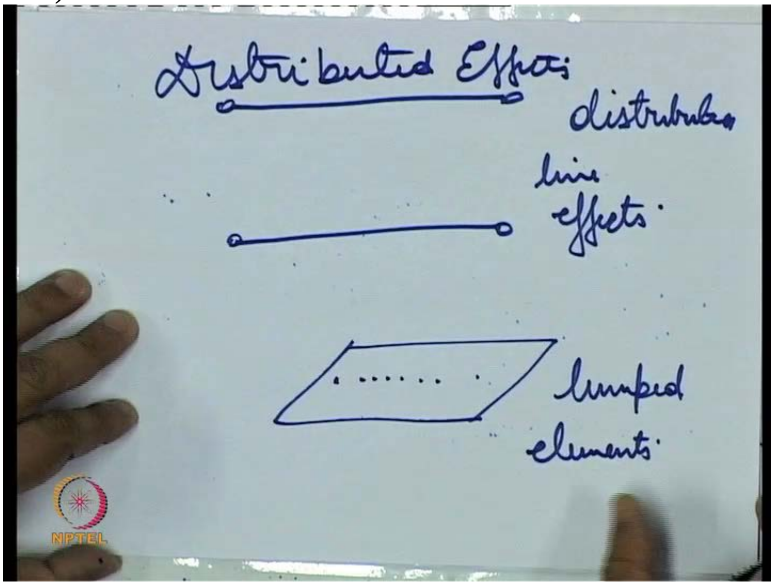

So for the wave nature we have already seen the solution. Let us see how we can deal with a circuit which has the distributed effects.

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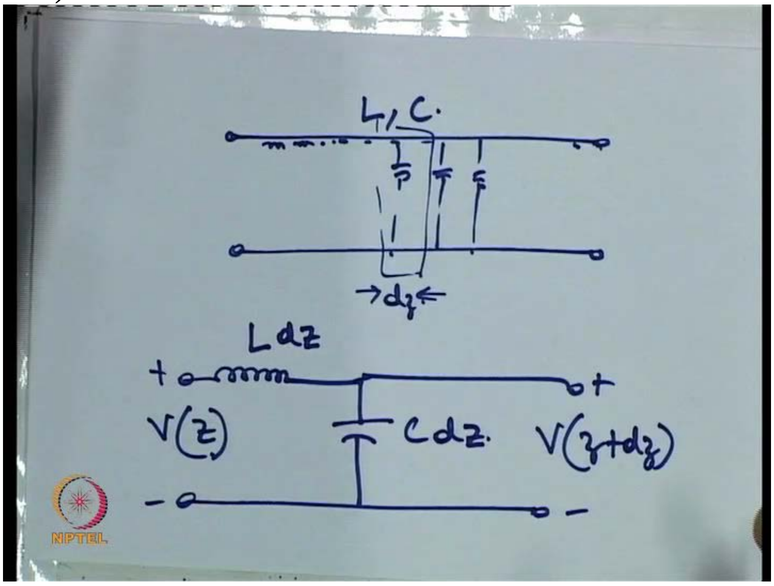

So to deal with a distributed effect, let us consider a long transmission line which has L and C as an inductance, series inductance and shunt capacitances per unit length. What this means is there are small small inductances all along the length of this line and there are also small small capacitances all along the length of this line and the problem is to find the solution when we have such very small capacitances in shunt and series inductance is present. As I said, you cannot approximate this with a single lumped impedance. Why? Because it will be like solving an infinitely long ladder network which is not possible.

Instead, if we just take a very small, a differential element DZ and represent it like this. So this is a very small element that is the series inductance and shunt capacitances are given like this. So now if we apply the Kirchoff's current law now this is very small element which we are assuming can be divided no further, this element if we apply Kirchoff's current and voltage laws then we get equations like this.

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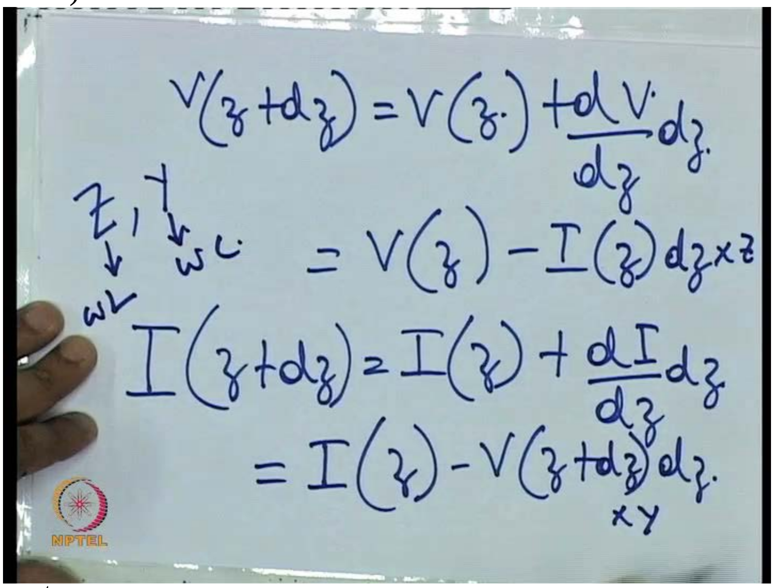

So this is the 1st equation using KVL. And using KCL, we get this as the equation. So here, Z and Y are the impedances and admittances per unit length. For a lossless line, Z will get converted to omega L and Y will be converted to omega C. So now if we solve these 3 equations, the solution that we get, the equation that we get on solving these 2 simultaneously questions, the difference early question that we get is something like this.

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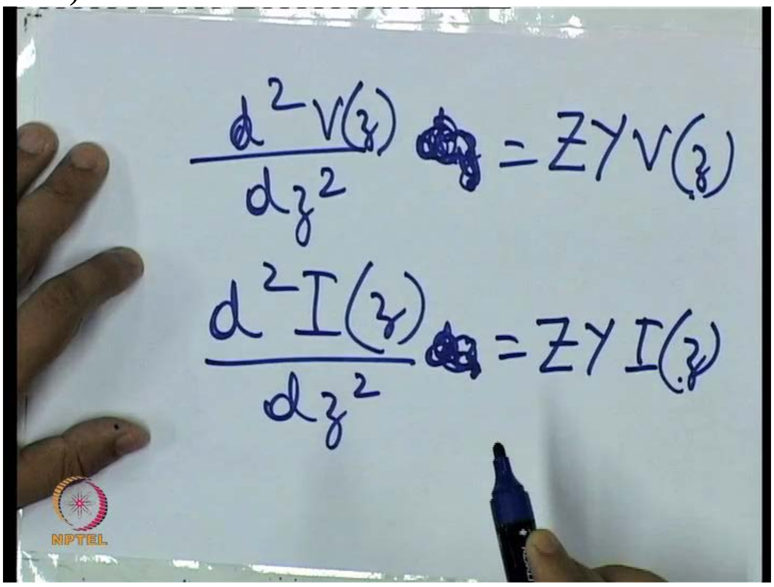

So this DZ is not there. This is a homogenous equation if you can ignore this scribble mark. This is a homogeneous a question. The solution of these, any of these 2 homogeneity questions will give solution or both, DZ and IZ. And the solutions are given as.

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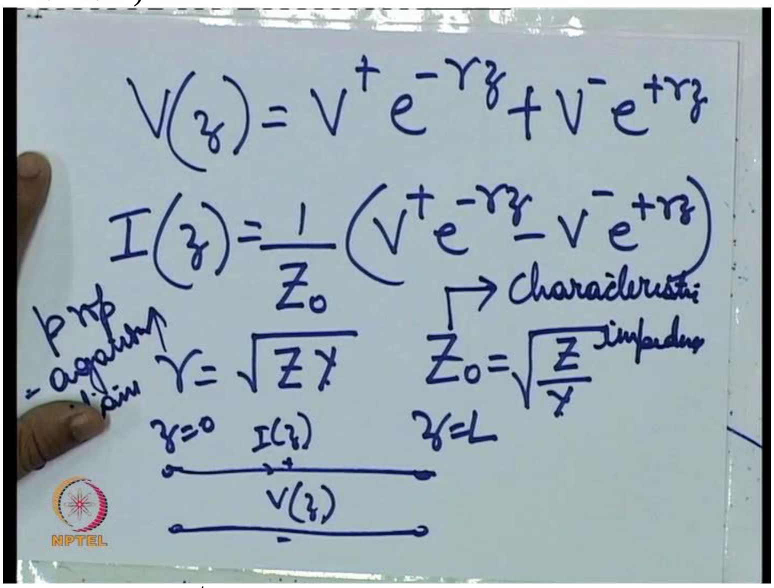

So this is the solution.. The 1st thing we note is that the world is along the…so Z, here Z is like this is our transmission line, then at the beginning we have Z equal to 0 and at the end we have Z equal to L. And VZ that is the voltage at any point along this transmission line is given as the sum of 2 waves, 2 exponential terms. So these are like waves. And the current IZ is equal to the difference of 2 waves and the Zo is a constant, it is a constant for a lossless line but for a lossy line, it is equal to this equation. So these are 2 new terms that come, Z0 and gamma. Gamma is called as the propagation constant.

And Z0 is called as the characteristic impedance. So we will see that these 2 terms, gamma and Z0, they completely characterise the transmission line.

Now there are some special cases possible. For example, for lossless lines, Z0 will be simply given as the ratio of L upon C and would be constant irrespective of the frequency. And for the lossless line, the value of, will be given like this.

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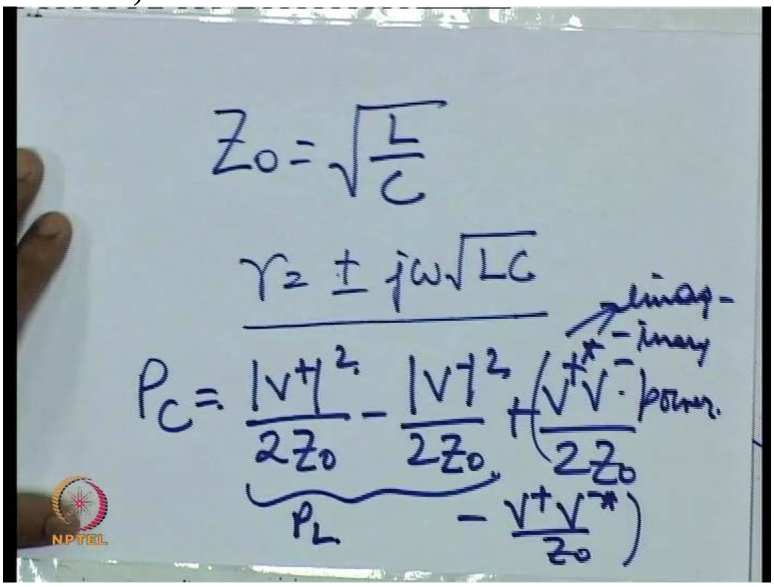

So this is again, we see the solution is non-dispersive because gamma is directly proportional to omega as we had seen. One interesting relation that often comes is what is the total complex power transmitted. The complex power transmitted can be can calculated from the equations that I just showed to be equal to. This term is the real power transmitted or the loss happening in the circuit and this term is the imaginary power or stored power. So these were some basic concepts about microwave engineering and how we deal with the problems that come up when we have microwave devices. So there are 2 major features of microwave engineering. One was the wave nature for which we had the solutions, various wave solutions like like the TE, TM and TEM waves and the other is the distributed effects for which we had to solve the transmission line equations.

On solving the transmission line equations, we saw that we had some new terms like the propagation constant, characteristic impedance. Then the voltage this concurrence had 2 independent terms like V + and V -. V + is usually referred to as the incident wave and V - as the reflected wave. Now, microwave engineering is all about how we manipulate the incident and reflected waves. In the next module, we shall be further discussing something parameters associated with microwave engineering. Thank you.