Transmission lines and electromagnetic waves
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Lecture – 14
Transmission Line Limitations and Maxwell's Equation

We will get started. So, it will be the last lecture for Transmission Lines ok. So, we will try to wrap up, but we will wrap it up with a few questions ok. So, the questions will be open and then you can think about it when you have time alright, because there has to be a motivation for you to study further about this. So, I will open up a couple of questions and then allow you to think over a period of time alright has to what can happen.

So, the first thing I will do is pick up where we stopped, in the last class in the demonstration ok. We looked through the data sheets of different cables ok. And, I am picking up some value from the data sheets of these cables and I would like to do a couple of calculations alright to just highlight where we are headed ok. So, I am going to start with a problem ok.

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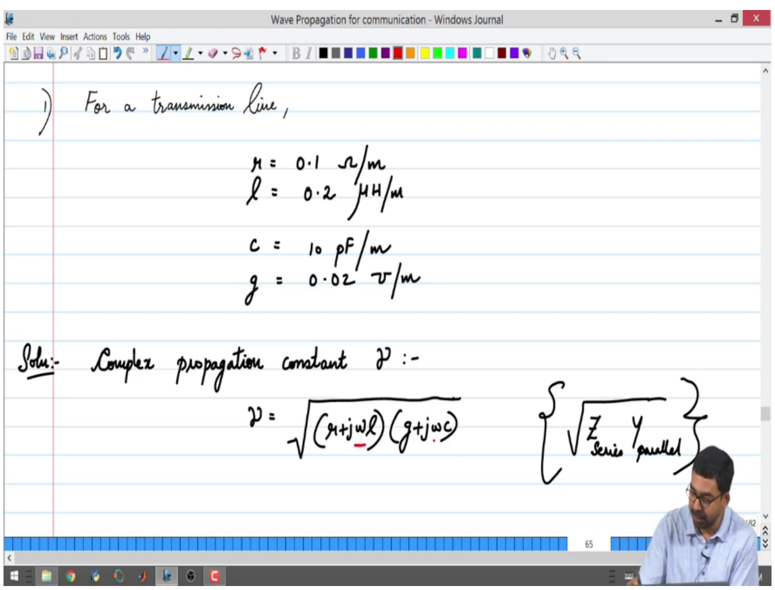

So, for a transmission line in this case we used coaxial cables ok. We had a the value this I have taken from one of the specifications sheets right seems rather high ok. l was 0.2 $\mu H/m$ $\mu H/m$, capacitance p order of 10 pF/m pF/m, g is 0.02 (Refer Time: 02:11). Please note that this is just one of the cables that I took, seems to be a particularly poor cable or the frequencies at which these data have been taken are quite high ok.

But, it serves a specific purpose for this lecture, so I have picked these values. So, I have r l g and c ok. So, there are two things that one can immediately calculate: one is going to be the characteristic impedance. You could do

$$Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}}$$

But, let us now go ahead and try and see whether we can calculate complex propagation constants ok. So, I want to calculate complex propagation constants.

ok I want to calculate complex propagation constant γ and I know that from our previous lectures

$$\gamma = \sqrt{(r + j\omega l)(g + j\omega c)}$$

Another way to remember this which will be useful for the later part right is square root of series impedance multiplied by parallel admittance of your equivalent circuit. So, in this case r and l will be in series, g and c will be in parallel this is another way to remember ok. Means that in order to calculate γ, I need to have idea about one more parameter which is ω ok. I need to know the ω values for calculating γ right.

We can start with a very simple case, suppose we assume that r l g and c are going to be frequency independent, we can make a simple assumption ok just to see what happens right. And, we can try and see what is the value of the complex propagation constant for different frequencies ok.

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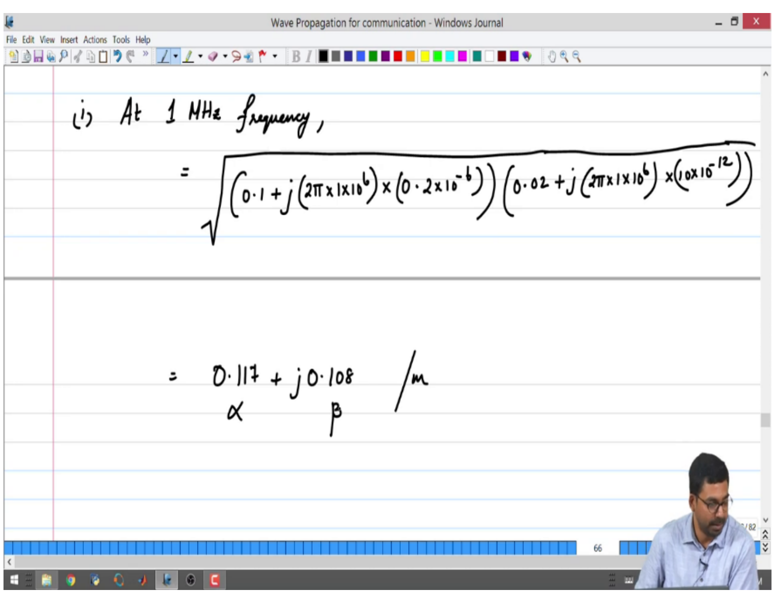

So, we can start with a low frequency say 1 MHz. So, the experiments that we conducted in the demo session were at a 100 MHz, but we are starting just at 1 MHz MHz ok ok. At 1 MHz frequency I will be having

$$= \sqrt{(0.1 + j(2\pi * 1 * 10^6) * (0.2 * 10^{-6}))(0.02 + j(2\pi * 1 * 10^6) * (10 * 10^{-12}))}$$

$$= 0.117 + j0.108\ /m$$

Here we already know that the form of γ The real part is going to be attenuation constant alpha and the imaginary part is going to be your phase constant beta ok. So, your ending up with some value of attenuation constant with this 0.117 ok.

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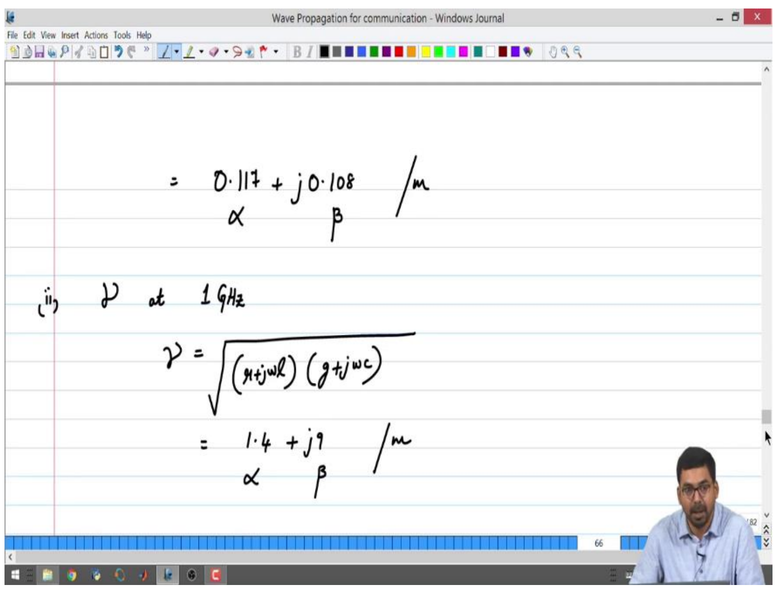

Now, let us find out the propagation constant at 1 GHz ok. Now, we keep all the parameters fixed assuming that all the parameters are fixed, it is an assumption in practice it may not be so right. But, assuming that all your r, l, g, c are going to be frequency independent and I just changed the frequency, I will have

$$\gamma = \sqrt{(r + j\omega l)(g + j\omega c)}$$

I immediately notice that, you know ω is present in a numerator which means that a I am going to be having higher values of ω plugged into this equation. As a consequence, I should expect that my alpha values are going to be higher ok.

I do not want to substitute once again, you can substitute and the value that I have is $1.4 + j9\ /m$. Once again the real part is alpha and this is the phase constant ok. The first thing that we notice is that in the transmission line for a lower frequency the attenuation constant is very low. For high frequency in the same transmission line assuming all the parameters are fixed, the attenuation constant is very high, just consistent with the data sheet that we were seeing for the cables. However, I have just picked one of the poorer cables at a particularly bad frequency. But nevertheless, the tendency is

$$\gamma = \sqrt{(r + j\omega l)(g + j\omega c)}$$

Any increase in γ invariably is going to drive your alpha ok which means that for higher frequencies the question becomes, is a wired transmission line approach suitable or not?

Ok. Because, as your bandwidth requirement will keep increasing for communication you will notice that the transmission line which has a forward and a return path consisting of wires will invariably end up having higher and higher amounts of attenuation, this is something that you cannot deal with easily. The only way to deal with this in practice is probably to build better cables, this is one approach. The other approach is to have some amplification in your lines. For example, when your signal deteriorates over a distance, at that distance it keeps some kind of an amplifier which converts say electrical energy and transfers it to the signal.

So, you have to know the higher magnitude of the signal that is traveling. So, you will be having in some way some repeating amplifiers of some kind in your transmission line ok a, But, suppose you want to go to extremely high frequencies or extremely high bandwidths then the approach of transmission lines is going to be questionable at best ok. So, we already noticed that even with some practical values GHz frequency operations are already very very tough in wired cables based transmission lines ok. This is the first thing and just to give you a feeling we moved from 1 GHz to 1 MHz ok.

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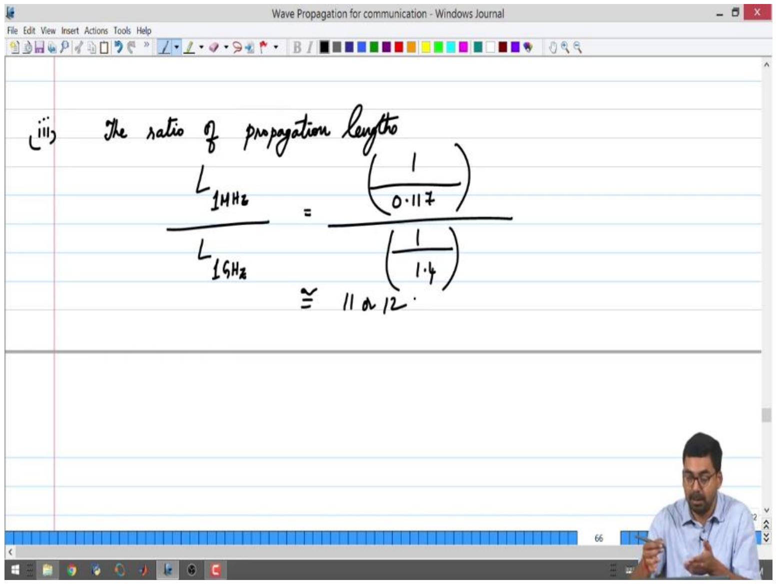

I mean 1 MHz to 1 GHz ok, that is about 1000 times increase in frequency alright and we can also do the other thing right. From this we could always calculate the ratio of the propagation lengths ok ok. So, we can say that L_{1MHz} is the propagation length at 1 MHz divided by L_{1GHz} can be calculated. You can just take the real part of your propagation constant. So, you can do 1 by alpha for the numerator for 1 MHz, 1 by alpha for the denominator for 1 GHz.

So, you will be having

$$\frac{L_{1MHz}}{L_{1GHz}} = \frac{\frac{1}{0.117}}{\frac{1}{1.4}} \approx 11 \; or \; 12$$

So, the propagation length at a MHz for this particular transmission line is about 11 to 12 times higher than the propagation length at 1 GHz which means that at higher frequencies you will need to have amplification much much more closer placed to each other.

So, if you want to have some repeaters or amplifiers based periodically on your transmission line, at higher frequencies they have to be closer to each other to provide the same power output ok. So, this is one direction of thought, as your bandwidth requirement increases or at higher frequencies how does one start doing communication and how does the theory change? This is a broad question ok. So, this is the direction in which we are heading, so, the direction that we are heading towards is a is there a need to use only currents and voltages or can you make use of electromagnetic fields ok.

And, in case we end up using electromagnetic fields because they can travel at the speed of light in vacuum ok and they can travel over anonymous distances even in vacuum ok. If we are (Refer Time: 13:00) electromagnetic fields, then is there a considerable change in the theory that we have already learned? Ok. This is the question and the broad answer to that is no, there is no change in the theory ok. Now, in the next few lectures we will be starting with Maxwell's equations because that will be the starting point for this course. The derivation of Maxwell's equations, the Gauss's law, Ampere’s Faraday's law should have been covered earlier in your undergraduate, in your second semester extra.

But, here we are beginning with where you left Maxwell's equations right. Now, if I try to use Maxwell's equations and try to find the solutions to Maxwell's equations, is there a similarity that I noticed between transmission lines and Maxwell's equations? Can I use similar computer programs to solve Maxwell's equations? Do the r, l, g, c have equivalent in Maxwell's equations? The propagation constant is it going to be similar in Maxwell's equations? These are the broad questions all right and the answer to that is everything is a transmission line ok. And, the philosophy is everything is a transmission line irrespective of whether you use wires or not.

The only thing that matters is whether you are going to be using voltages and currents or electromagnetic fields. But, once you make the switch, I will show that they become nearly identical ok. There are a few quirks to electromagnetic fields right, but other than that you will see that the vast majority of the theory remains the same. So, if you understand transmission lines very well, chances that you will understand Maxwell's equations as well are very very high. So, this is one aspect, one direction in which we are going ok. I will also pose a question because now we are wrapping up transmission lines, I will also pose a question for you to think about slowly ok. This need not happen during the semester, it can be during your semester break or it can be any other time alright.

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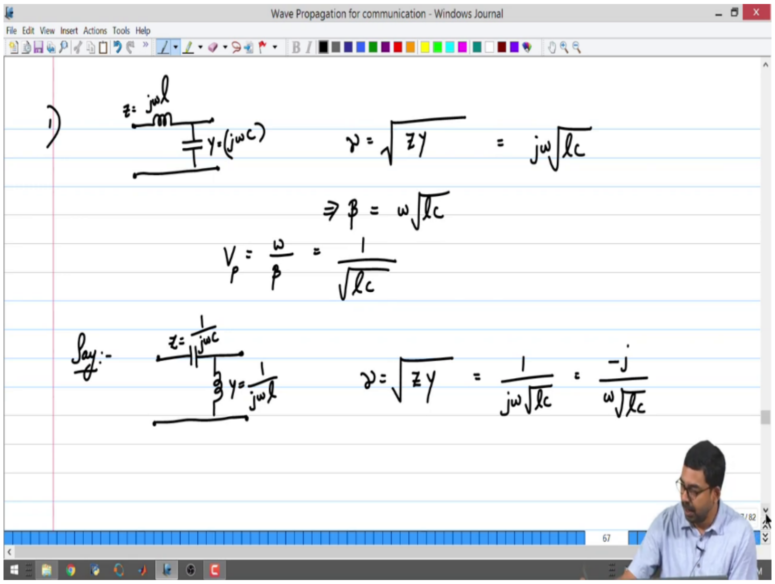

One of the things that we heard earlier learned or begun with in transmission lines is the circuit model of a section of a transmission line. And, we drew a series inductor for a lossless section ok and we had a parallel capacitor alright. And, then we had jωl to be the series impedance right and your parallel admittances is again jωc, this is what we had before alright. From here we could always find out

$$\gamma = \sqrt{ZY} = j\omega\sqrt{lc}$$

is something that we have already seen ok.

In this case since a γ is having only an imaginary part, you have only a phase constant, you do not have any attenuation constant, just consistent with the model you do not have any r and g. This was the most ideal circuit representation of a section of a lossless transmission line ok. In this case one can go ahead and write which implies there is only beta, $\beta = \omega\sqrt{lc}$ right. And, we also know that a velocity is ok, that is why we have used the term velocity. The more correct term that I had mentioned in one of the lectures is phase velocity right is

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{lc}}$$

So, ω will have the units of rad/m, beta will have rad/s. So, we will end up having m/s, but this is the phase velocity. And, we already know that this velocity is

$$v_p = \frac{1}{\sqrt{lc}}$$

These are some things that we are already aware of should be on our fingertips by now ok, but let us twist the problem very little alright. Let us just say that I am going to be having an equivalent circuit, but the components are wrongly placed ok. The components are switched ok, they could be switched by accident or they could be deliberately switched alright.

Because it is a model, we can plug in anything and try to solve for the voltages and currents ok. Now, suppose I have switched the position of the capacitor and the inductor ok, let us see what could happen. First of all the series impedance ok

$$z = \frac{1}{j\omega c}$$

the parallel admittance will become

$$y = \frac{1}{j\omega l}$$

This is the first thing that we notice ok. The next thing that we could do just a repeat of whatever we did for the original transmission line is we could calculate the complex propagation constant

$$\gamma = \sqrt{ZY} = \frac{1}{j\omega\sqrt{lc}} = -\frac{j}{\omega\sqrt{lc}}$$

I am getting a value for the propagation constant a, but then I can say that the propagation constant is made up of an alpha and a beta and I do not have an alpha here, because I do not have resistors right.

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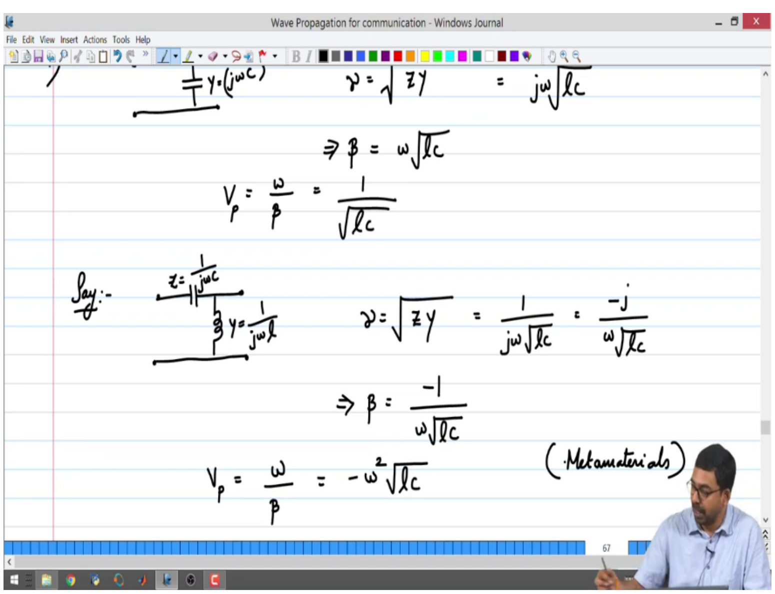

So, this means I have only an imaginary part which means my phase constant right is going to look like

$$\beta = -\frac{1}{\omega\sqrt{lc}}$$

The phase constant looks negative ok. We still do not know what to make out from this alright, but there is one more step that we did before, we calculated the phase velocity ok, maybe we will calculate that also and see what happens alright. So, we can say that the phase velocity is

$$v_p = \frac{\omega}{\beta} = -\omega^2\sqrt{lc}$$

Remember all we did was just switch the position of the components and then you end up with something very ridiculously complicated. What happens here is the phase velocity looks negative, this is the first thing that we noticed compared to prior results that we have. On top of that the phase velocity depends on the square of the frequency, that means, for different frequencies you are getting different squares, I mean different velocities, phase velocities ok. Now, one can also ask a question: does it make any physical sense? If your phase velocity is negative does it mean that the information is going from source to sink? Does it mean that it is going from sink to source?

All these questions will start coming into the mind, I just wanted to sow the seeds at the time I am wrapping up transmission lines ok. All I have done is switch the positions of l and c and you can already see that something bigger is happening over here ok. So, I will stop here, I will allow you to think for the remaining time when you have the right. So, this may look absurd ok, but it actually has some deep physical consequences. And, what these are known as are metamaterials ok, somethings you know which exhibit some weird properties. So, negative phase velocity, but positive group velocity, negative phase constant ok extra.

So, in the simplest terms these are metamaterials. So, since I am wrapping up transmission line, I just wanted to put a word that is not the end, you can always fiddle with the model and arrive at some you know something big and also start analysis ok. So, you can go back, you can see about these, can also see what is a phase velocity and what is a group velocity, does the information travel from source to sink, does it appear to be reversed all these things. So, these questions should be there in your mind. So, that is the whole point of putting this ok.

So, now that I have completely wrapped transmission lines right, the big question I will proceed to wireless systems alright or wireless power transfer involving Maxwell's equations.

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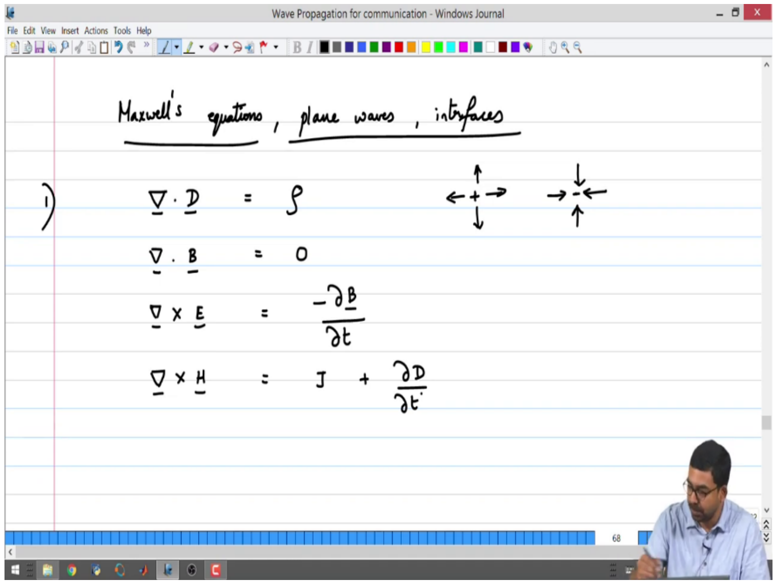

So, the broad topics that we are going to be seeing till the next quiz is Maxwell's equations, solutions to Maxwell's equations and plane waves. And, we will also be talking about interfaces, these are the three things that we will be seeing prior to the next quiz ok. Now, I am not going to go into the derivation of the Maxwell's equations, this is something that should have been done much much before this course ok. So, I am going to start with Maxwell's equations and I am just going to revise a few things and then I am going to proceed to make the analogy with transmission lines.

So, I will start with writing down Maxwell's equations ok. So, I have the Gauss's law

$$\nabla . D = \rho$$

Depending upon the sin of the ρ ok, I could have fields emanating from charges. So, ρ is the charge density, yeah some convention is followed, plus means that I am having fields diverging out and minus means that I have fields converging in ok, the convention that we follow. So, this is Gauss's law, it just says that the divergence is going to be proportional to the charge density. That is ok. So, higher the charge density more diverging out your fields are going to be from that point or more converging they are going to be ok.

Now, the other Gauss's law for magnetism is

$$\nabla . B = 0$$

Since, there are no magnetic monopoles you do not have diverging magnetic fields. This means that your magnetic fields are going to be in the form of loops. So, the divergence is implicitly 0, this is the other Gauss's law ok. Now, when we are writing these alright, I will write down the remaining equations and talk to you about the quirks involved in these equations. I also have the two curl questions right, let us make it

$$\nabla \times E = \frac{-\partial B}{\partial t}$$

and I have another curl equation

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

ok.

So, I have written Maxwell's equations, there are two curl equations and the two Gauss's laws ok. Now, if you look at these equations there are only two equations that talk about the coupling between the electric and the magnetic fields. Those are the two two curl equations ok. So, on one side you are having E, on the other side you are having B, but in order to be clear we have to define what is this D and B also, because those are appearing over here. So, to give the constitute relationships we can say that

$$B = \mu H$$

$$D = \epsilon E$$

where ϵ is the permittivity ok.

And, the unit is F/mNow already you should be able to figure out where we are going right. The unit is F/m ok, it has the same unit as the distributed capacitance in the model of your transmission line. μ has the unit of H/m, it's the distributed inductance ok. E has the unit of V/m and H has the unit of A/m ok. I think some similarities should be clear, I think we are getting there alright. Now, there are some quirks in the way we have written the equation and we have to sort it out before proceeding further. In the two curl equations on the right hand side I have used time derivatives.

I have written these equations in time domain ok, I have written these Maxwell's equations in time domain because I have used time derivatives on the right side. So, I want to be very clear about it ok. If I am writing the derivatives in time domain means that my electric field is changing with respect to time alright. Remember that in your telegrapher's equations for transmission line you had $\frac{\partial V}{\partial t}$, you had $\frac{\partial I}{\partial t}$ alright. We are considering voltages and currents changing with respect to time. Here similarly electric and magnetic fields are changing with respect to time and you want to represent it accurately, that means, the first equation has to be written as

$$\nabla . D(t) = \rho(t)$$

Need to be very careful about this ok.

At some instant of time you are calculating the divergence, at a tight instant of time you can calculate the charge density ok.

$$\nabla . B(t) = 0$$

At any point in time you are going to be having magnetic fields which are in loops ok.

$$\nabla \times E(t) = \frac{-\partial B(t)}{\partial t}$$

$$\nabla \times H(t) = J(t) + \frac{\partial D(t)}{\partial t}$$

And, just to be clear this is conduction current density. If your $\rho(t)$ is non-zero, you can have J(t), ρ means you have some charge density. If there are no charges there is nothing for it to conduct, so, you will be having 0 conduction current density. So, J depends directly on ρ ok and

$\frac{\partial D(t)}{\partial t}$ is your displacement current density.

Now, we have changed all these to the time domain, but then we have to look at the characteristic equations, maybe not the expressions for displacements and the fields also right. Now, we have to look at it in a more objective way,

$$B = \mu H$$

It is a very very tricky thing, D is equal to ϵ is a very tricky expression to write ok.

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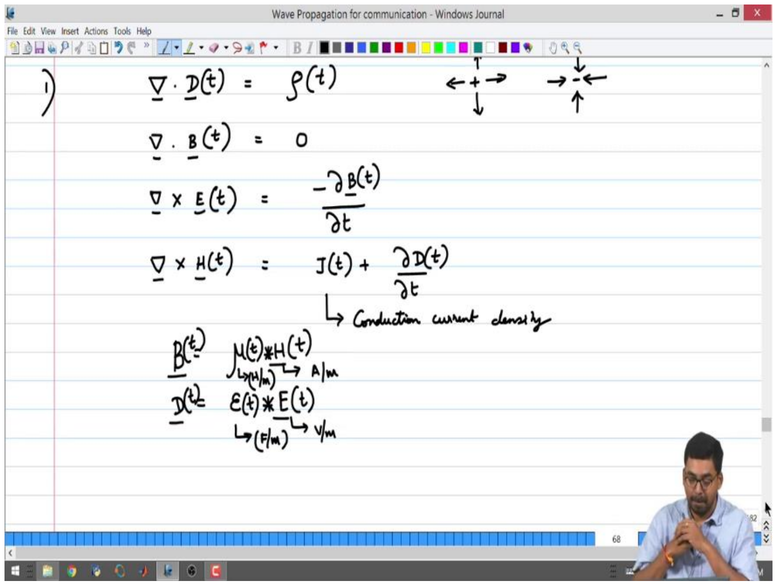

Now, let us now be very consistent and say that B(t) is what we are writing down and D(t) is what we are writing down ok. On the right side I have H(t) and I have E(t) ok ok. Now, here once again the correct way to do this is not by multiplication. One of the things that we have to now understand is just like l, c, r and g, here we are not having r and g yet ok, we are having ρ and J, but we will come to that later.

Suppose, we start with electromagnetic fields in some lossless medium, the lossless medium will just have ϵ and μ ok. But, one of the things that we know now how to graduate right, previously we used a fixed value of r, l, g, c to calculate propagation constructs. But, in reality r, l, g, c will all depend on frequencies. Similarly, μ and ϵ should also depend on frequencies, if they depend on frequencies we have to write this correctly as $\mu(t)$, $\epsilon(t)$ ok. Because, time and frequency share a Fourier transform relationship, you will have to be very clear and say that its $\mu(t)$ and an $\epsilon(t)$, but there is another quirk.

$B = \mu H$, usually it's written in the frequency domain ok and $D = \epsilon E$ is written also in the frequency domain. And, when you go from multiplication in one domain and you take a Fourier transform, you have to represent this as a convolution alright. So, the correct way to write this is actually a convolution alright. So, you see now we are getting into more details than in transmission lines and that is how it's going to be ok. So, we started with the Maxwell's equations right, we have written them in time domain and then we have written the constituent relationships for B and D in time domain alright.

If μ and ϵ are going to be frequency dependent then the correct way of writing Maxwell's equations with the constituent relationships is actually using a convolution operator for D and E.

$$B(t) = \mu(t) * H(t)$$

$$D(t) = \epsilon(t) * E(t)$$

This is the first thing that you have to remember alright. Now, this also tells you a lot of things about what can happen alright. Since, we are not now not talking about only wires, we are talking about big media, we are talking about bulk media extra right. And, anything will have some ϵ and μ right for example, vacuum which is defined as absence of anything technically still has ϵ right.

It has the $\epsilon = 8.84 * 10^{-12}\ F/m$ ok and again vacuum, which does not have anything, has some mu, just $\mu = 4\pi * 10^{-7}$ right. It means that these are properties of the material at all points in space, at every instant of time you can figure out what are the fields ok. So, these are some really distributed parameters ok over large areas of space and even in vacuum these things do not become 0 ok.

So, this will have some lots of questions, but I think you can think about the same varieties of ways. The first thoughts that we can have about are what are these kinds of materials that we can have? Now, we are dealing with materials because we are dealing with infinitely large media where you can have electromagnetic fields, where you can have μ and ϵ alright even in vacuum. What other kinds of materials could you have? So, we will start with these constituent relationships and try to identify the kinds of materials you can have ok.

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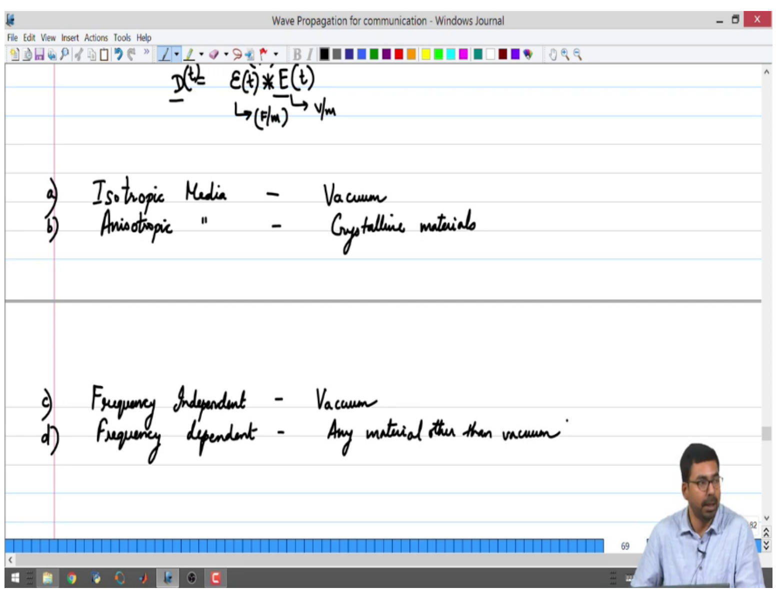

The simplest kind of material that you can have is known as isotropic media ok. Now, isotropic media means that you have the same value of ϵ and μ in all directions. Now, you see what happened previously, we had introduced time, now we are introducing space into the material parameters. Now, what happened is r, l, **g**, c are not only a function of frequency, but also are becoming a function of position ok. So, this needs some deeper thought, because previously this direction is something that we did not consider very much, you know intensely.

Because, we know that the direction of the I mean the wire is going to be this direction of the transfer of voltage or current extra, but now we do not have any wire alright, that means, we have to consider in all directions what is going to happen at all instances of time. So, it makes things a little bit more complicated or it could make things a little bit more interesting ok. Isotropic medium means that you are having uniform properties in all directions, an example is vacuum ok which already gives you the thought about what other material could be in terms of space, you could have anisotropic media, which means that you do not have the same value of ϵ and μ in all directions alright.

In solid state physics near undergraduate you may have studied crystal structures and crystal lattice, specifically you must have studied about the Bravais lattice and Miller indices and all that ok. You must have dealt with what are known as crystalline materials and in the crystalline materials specifically we place a lot of emphasis in the undergrad on the simple cubic system alright. In the simple cubic system, at the corners of the cube you will be having atoms positioned ok, atoms of a material position alright. And, that is one way of looking at anisotropic medium alright. If you have a cube, the spacing between the two atoms in the horizontal direction is the same as that in the vertical direction is the same as that in the depth or in the you know other inside direction alright depth right.

But, if you start looking at the nearest neighbour along the diagonal, the face diagonal is a times square root of 2. So the atoms are further apart in the case of phase and in the case of body diagonal you will have the atoms spaced further apart as a square root 3. Now, if the atoms say you would be studying about silicon mostly in this solid state course and you would be studying about positioning of the silicon atoms. And, the silicon will have some value of permittivity and permeability ok. But, if you start looking at these crystal structures you will notice that the rate at which the silicon atoms will occur when you travel in the x direction ok will be different than what will happen in the diagonal, will be different than what will happen in the body diagonal direction extra.

So, in some sense you can say that the density of the materials in different directions is going to be different alright. Equivalently the permittivity and permeability in different directions are also going to be different because they are further apart in different directions right. So, anisotropic media as such media alright, where you have along directions different density of atoms ok. So, an example for anisotropic medium is a crystalline material ok. These are tough materials, that is you have to think about what will happen in every direction alright. And, you have two more categories, you have frequency independent.

Frequency independent materials, the only example that I am aware of is vacuum ok. In practice you will not have frequency independent materials, you will have frequency independence in a small range of frequencies between 1 MHz and 2 MHz. There is no significant change in ϵ μ or r, l, g, c parameters ok. So, in a small range that can be frequency independence, but in a broad range for example, we went from 1 MHz to 1 GHz using the same values of r, l, g, c is not usually appropriate right. You multiply the frequency 1000 times you will have to recalculate what is r, l, g, c with standard materials ok.

So, frequency independent is a good assumption for doing you know paper level work right and to simplify math it's a fine it's a fine way to do it right then, obviously, you have frequency dependent ok. So, I am just going to put any material other than vacuum is going to have some frequency dependence ok. So ϵ, μ everything is going to be frequency dependent for most materials other than vacuum itself right. So, now you can think about a small thing: what do these frequency dependence mean, all these things? There can be a few questions that you can slowly start thinking about.

For example, you know when you go to a doctor you know with a broken bone and they want to take an X-ray ok. So, the X-ray is a higher frequency alright or you can say that it is a different frequency than what we are used to with the eyes. We see visible just about 400 to 700 nanometers in wavelength, X-rays are smaller wavelengths right. But, one could ask why not use X-rays right and what is the advantage? Well the specific advantage in this case seems to be that the permittivity and the permeability of the skin seems to be different for visible and seems to be different for X-rays.

So, the visible light is not passing through the skin ok, significantly and we are not able to pick up scattered radiation through the eyes, but X-rays seem to penetrate through the skin. So that means that the skin has different values of permittivity and permeability for X-rays and permittivity and permeability invisible is different for the skin. Same way for the bone ok in the visible it could have some permittivity and permeability, but in the X-rays region it has a different permittivity and permeability right. So, differences in properties I mean with respect to frequency are very useful, ok, but they make the math a little bit more difficult.

But, in the majority of the cases in this course we will be considering frequency independent isotropic media because that is the simplest for us to understand all the phenomena. Slowly, we will introduce some anisotropy and we will also introduce some frequency dependence. But, when we are talking about anisotropy, there are many many many kinds of anisotropy possible. So, I do not think we will have time to go through each and everything in detail. But, you should have a thought that materials can be anisotropic, the way to analyze them can be slightly different ok. But, we will see to the best whatever we can do, know a little bit according to paper and pen what is convenient, we will do that ok.

Now that we have written down Maxwell's equations, we have written it down in the time domain and we have also classified the media. There is one last thing that we can do before we wrap up. And, that is to establish the clear relevance or the clear connection to transmission line ok. So, let us throw out $\nabla.D$ & $\nabla.B$ for the time being ok and let us also start looking at cases where you do not have free charges ok.

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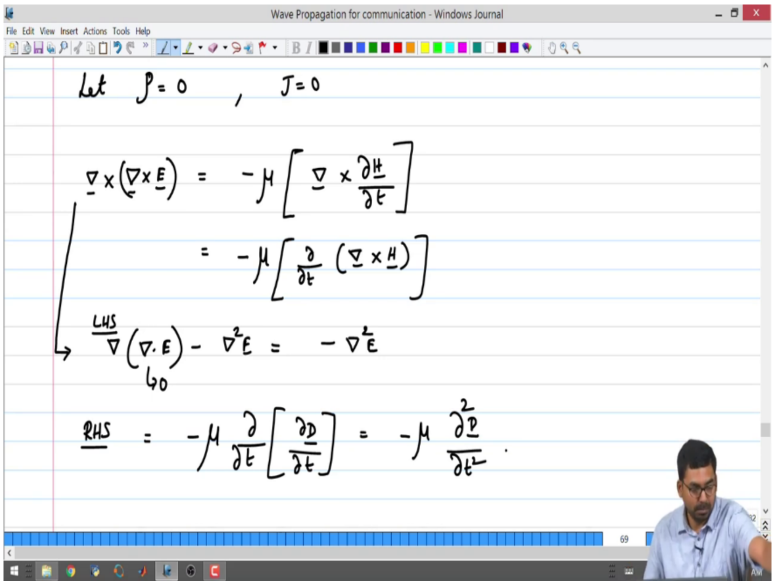

So, we will start with the simplest case let $\rho = 0$, that is you do not have any free charges. There is no charge density, that means, you do not have diverging electric fields extra, you have only circular loops of electric fields ok. This also means that your conduction current density J becomes equal to 0, $J = \sigma E$, alright and here we are having ρ = 0. So, which means that you do not have charges, we will just have no conduction current, we will start with this ok ok.

And, I will look at only the curl questions alright. So, I am going to take the curl equation $\nabla \times E$, I will write it in less detail because you know all the details it depends on time. I mean you have to use convolution all these things now you are aware of right. But, I just want to say that I have a coupled partial differential equation right $\nabla \times E$ which is

$$\nabla \times (\nabla \times E) = -\mu \left[\nabla \times \frac{\partial H}{\partial t}\right]$$

$$= -\mu[\frac{\partial(\nabla \times H)}{\partial t}]$$

Just similar to your telegraphs equations and we will break it down in the next class and show that there is one to one correspondence ok.

So, I will just write down the expansion of the left hand side directly ok so,

$$\nabla(\nabla . E) - \nabla^2 E = -\nabla^2 E$$

The right hand side will become

$$= -\mu \frac{\partial}{\partial t}\left[\frac{\partial D}{\partial t}\right] = -\mu \frac{\partial^2 D}{\partial t^2} = -\mu\epsilon \frac{\partial^2 E}{\partial t^2}$$

$$\nabla^2 E = \mu\epsilon \frac{\partial^2 E}{\partial t^2}$$

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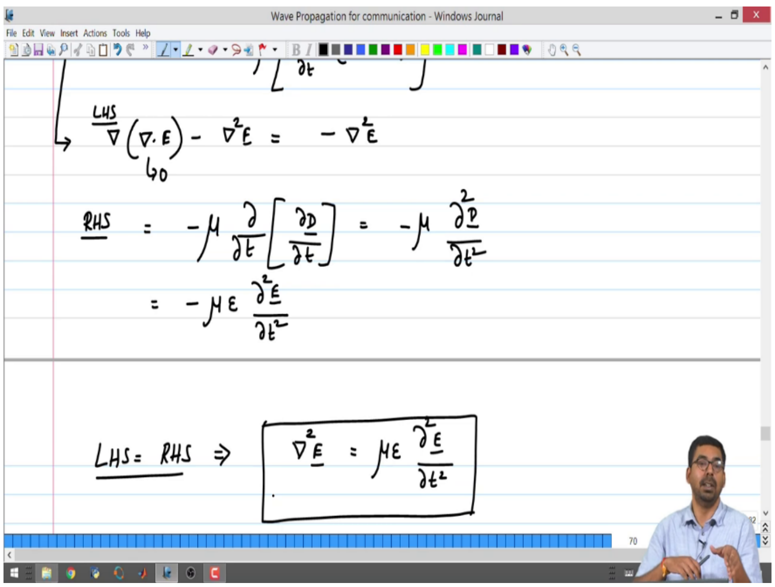

We will take a little bit of time to grasp this, but what we have got is exactly the wave equation that we had from the transmission line alright.

On the left hand side you would have had $\frac{\partial^2 V}{\partial z^2}$ instead of E just put v alright, del because you did not have all spatial directions there. Just pick one Cartesian coordinate $\frac{\partial^2 V}{\partial z^2}$ on the right hand side, μ will be replaced with l, ϵ will be replaced with c, $lc * \frac{\partial^2 V}{\partial t^2}$ ok. So, there is some direct equivalence going on between these Maxwell's equations and the transmission lines ok, so, these are not very different things. So, the theory that everything is a transmission line could actually be true.

I mean we could always look at everything as a transmission line irrespective of whether we are communicating with currents and voltages or you are communicating with simply electromagnetic fields and Maxwell's equations. In fact all the circuit loss can be derived from Maxwell's equations, so, there is no surprise over here ok. So, we will stop here. In the following classes what we will be doing is we will be going over these concepts in detail. Just like in transmission lines we will try to solve Maxwell's equations using computers.

We will try to solve the wave equation using the computer, try to figure out boundary conditions. There we have short circuit, open circuit alright, here we will have equivalent conditions alright. And, then we will be having some attenuation constants alright, amplification, we had the square root of r g coming into the picture, we will be doing all that. Once we establish the clear equivalence alright, then we will be going for the differences between this and that which is directions, polarization and all these topics and then we will go to interfaces. So, I will stop here.