Electromagnetic Theory
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Lecture - 69
Waveguide

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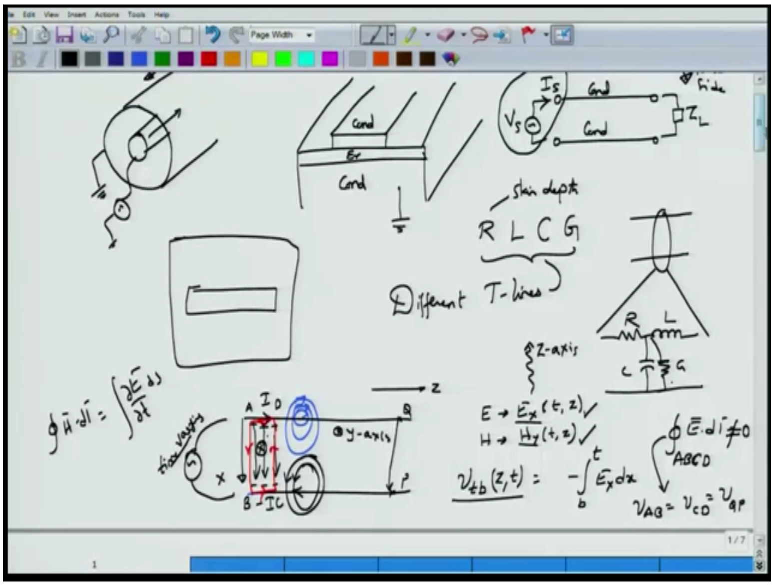

In this module, we will discuss what is called as a waveguide. Now, before we go to waveguides, let us just review couple of points from transmission lines. So, in the last few we have been discussing transmission lines and most transmission lines have different physical structure. For example, a simple coaxial cable would be made out of two conductors, one an inner conductor and one an outer conductor, right.

So, they have different radii and then there is a material that is insulator filled between the two conductors and so, right. So, when you apply a current, so, when you hook up this one, you normally ground the outer conductor and then connect a signal source to this one, okay. So, when you do that there will be current going into the inner conductor and the same current would of course come back on to the outer, from the outer conductor.

A different kind of structure for a transmission line is something that I mentioned, which is called as a microstrip line, right. So, in a microstrip line, again you have two conductors, so this is would be the first conductor on the top and then there is also conductor, right at the bottom. So, this is also a conductor, this is also a conductor. Again, this conductor is quite large and there is a certain material insulator filling between the two conductors and we normally ground this particular conductor as well, okay.

The most familiar form of transmission line would happen to be a two wire line to which you can attach a load and then you can attach a source at one end. This is one conductor, and this is another conductor, right. There are additional ways in which you can create transmission lines. So, for example, this is something called as a strip line. In a strip line, what happens is that the centre conductor that we wrote, okay, in the case of a microstrip actually lies surrounded by a conductor.

It is something like a coaxial cable, but except that it is prepared on a printed circuit board and has a different cross sectional diameter. Of course, this cross sections or the diagram that I have shown here are the transmission lines are assumed to be uniform in the sense that as of march along the transmission lines. So, imagine yourself walking down the transmission line and at any point decide to cut the cross section, transverse cross section to your direction of the movement, you would see the same cross section.

So, these are called as uniform transmission lines, right. Regardless of what was the physical structure of the transmission line, we said that all of this can be said described if in terms of a certain distributed circuit that is a circuit whose resistance, inductance, capacitance and conductance were not at a particular point on the circuit, but they were rather distributed continuously throughout the length of the transmission line, right.

So, there are various way of calculating R L C and G. So for example we have calculated capacitance for the two wire line. We have calculated capacitance of the coaxial cable, right. We have also calculated the inductance for the two wire line, inductance for a coaxial cable and so on. The calculation of R and G are slightly tricky and not really important for our course and therefore we did not cover that.

But, they are also related to skin depth, something that we talked about it in one of the modules, right. So regardless of what was the transmission line, so these are all different transmission lines, okay. Let me write this as, just to emphasize this, so these are all different transmission lines. All of them were characterized by R L C G. R L C G for different transmission lines will be different.

But once you know R L C G this is a canonical structure that you assumed, right. So, this representation of a transmission line by two conducting wire holds for any transmission line whose R L C and G is know, why? That is so because, in this piece of wire, if you actually look at a particular region, right. Maybe you should at this region like this, right. So, you imagine that there is an R, there is series L.

Then there is a capacitance C and a conductance G, right, So, this is your canonical structure for a transmission line and what was the job of the transmission line? If someone were to ask, when you connect some source over here and you have a load over there, right. So, what is exactly this transmission line doing? What transmission line is actually doing is to convey the source voltage and a certain current, source current to the load.

In other words, it is actually carrying power from source side and then transmitting this power on to the load side, right. So this is actually transmitting power or power is related to energy therefore we can think of this transmission line or something that is transmitting energy from one end to the other end. So, these are energy transmitting devices. Although we have said that these are energy transmitting devices.

What really happens is that if you go to the electric magnetic field theory what you see that the moment you have some current launched there will be magnetic fields surrounding this. So, the magnetic fields are surrounding like this, right. So do not worry about what direction the magnetic fields are, you can find out that one by the right hand rule. Similarly, for the return current, there would be again magnetic fields, right.

So there would be again magnetic fields and what you can see is that if you call this as a z axis, the length of the transmission line and let us say vertical down as the x-axis, okay. What you see is that the transmission, I mean because the magnetic field lines form a loop, right. So, the magnetic field lies effectively come out of this page along the y axis, okay. So, the magnetic fields are along the y axis.

And for a uniform transmission line these H lines all lie along y and they would close around this particular current carrying conductor, okay. So, this current is the same current, so I and minus I, so there are, these magnetic field is which are curling around, right. The other thing that you have to notice is that because this is a conductor and this is another conductor separated by some insulator, there would be and what is current?

Current is nothing but flow of charges, right. So, there are charges which are flowing and then so the magnetic field lines will all curl around the current carrying conductor and there are two conductors for these transmission lines. So, one current is going in this way and the current is actually coming back. Now, if you look at not just the current, which is inducing the magnetic field, but current actually is nothing but, flow of charges, right.

And, there is a source that is applying a certain potential at least at the source end, right. So, there is a source which is applying a certain potential difference between two conductors. So, you have a top conductor and a bottom conductor and there is a potential difference applied, which means that this conductor, which has abundance of charges will be polarized in two different or polarized in opposite ways, right.

So, you have opposite charges. So, you have positive charges on one conductor and all the negative charges on the other conductor. The moment you have a positive and negative charges and remember that these are not just static. They are actually varying with time because the source potential is not constant and is varying with time. So, these are actually time-varying potential source or the voltage source that we have applied.

So, the charge distribution also varies over this transmission line conductors. But, the moment there are two charges of opposite polarity, there would be electric field, okay. So, you have electric fields down from one conducting wire to the another conducting wire, so let us call that as E x. And then you have magnetic field, right that would be along, so I am not going to write down the vector notation because they are not really important over here.

The magnetic field that would be there is mostly confined in that plane that is transverse to both x and z directions. The magnetic field lines are in the direction of H y. Now, an electric field which is directed along x, magnetic field directed along y, both of them varying with time as well as both of them varying with z, correct? Because we have seen that the potential on the transmission line or the voltage difference between the conducting plates on the transmission line is not constant.

It is actually a function of the length of the transmission line, so where on the transmission line you are situated that tells you the potential difference between the two. So, potential difference are you know between the two transmission, two points in the transmission line is actually dependent on the position of that point where you are taking along the transmission line, okay.

So, if you imagine yourself walking down the transmission line, what you would see if you carry a voltmeter is that this will voltmeter would read different values of the electric, I mean of the potential, if the time this constant. So, you imagine that time is held constant and you are able to walk along the transmission line with your voltmeter or an oscilloscope. What you would see that the potential is different at different points on the transmission line, right.

So, you have, so since the potential is different, the charge distribution will also be different, because current is also changing with time. Both the electric field E x induced from one conductor to another conductor as well as the magnetic field lines, which circulate the current carrying conductor will also be functions of t and z that is they would also be functions of time and space.

And if you now recall that potential difference between, say, top and bottom is now again function of z as well as t is given actually from the say bottom to top, right, and electric field, E x, d x, right. So, this is actually the potential difference between the two points, whether it is minus or plus that is a different matter, but the potential difference between two point on a conductor and it is a function of z is line integral of electric field, right.

Suppose we had come back to the electrostatic case, okay. So, I didn't have a time varying potential source connected to the transmission line. Then, if I choose a closed loop, okay. So, let’s say I choose a closed loop like this and then go around this particular loop, what would I see? I would actually see that the potential at these two points is constant because for the electrostatic case, the potential at say points A and B C and D, okay. So, I hope that you are able to see this one.

The potential taken around the loop A B C D would actually turn out to be, the electric field line integral A B C D, sorry, again I made a mistake. So, this is the loop, A B C D that you are taking and then you are taking the line integral of electric field around this path, okay. This would turn out to be equal to zero, right. So, this is a closed path A B C D that we have taken.

And then the line integral of the electric field around this closed path will be equal to zero because electric field from A to B is the same as electric field from C to D, okay. And then you of course no electric field between A D and B C, which also implies that the potential difference the two points A and B is actually equal to the potential difference between the points C and D and they would also be equal to the potential difference Q and P.

So, if you take this as Q and this as P, the potential difference here would be the same as the potential difference at points A B. So, in other words, for the electrostatic scenario, right, the transmission line actually acts like a conductor, whose potential is constant throughout its body, you know throughout the region.

So, this form an equipotential conductor or equipotential surface, okay, only in the electrostatic case, but that is not the case we are considering. What we are considering is time varying scenario. Therefore, for that situation, this loop, line integral over this loop will actually be non zero and this is to be expected. Because when you have a time-varying potential, right. So, electric field is changing with time.

This change in electric field must induce a certain magnetic field, right. So, from Faraday’s law, we know that these things would happen. So changing electric field would induce magnetic field, changing magnetic field would induce electric field and that has to come out. So, if in this loop, if you have an electric field which is changing then there will be magnetic field along y axis, okay.

And that magnetic field will be H y then H y will form a loop, which means that if you take the line integral of H then that would correspond to a certain current, right. Because the integral of H dot dl must be equal to the current and the current would consist of two components. One, the conducting current on the wire of itself, but in the region between there would be a current, which is, right.

So, there would be this current, which is called as a displacement current. So, what we see in all these things is to, if I want to summarize is that a transmission line is something that would actually I know have a electric and magnetic fields present on that because of the time varying potentials and currents that are present on the transmission line.

And most importantly, this E x and H y, which are you know they are on a two wire transmission line and these are the only two components that you can have or you can have E y and H x depending on how you would label this axis. And this E x and H y are polarized perpendicular, sorry, are oriented perpendicular to each other. Further, the wave is actually traveling or the energy that is actually traveling along z axis.

So, which means that you can actually define or you can describe this E x, H y and Z as a trio and this three would actually form the solution of Maxwell equation, wave equation, okay. And, E x and H y can be thought of as plane waves. So, in other words because E x and H y which are plane waves they would also correspond to have a corresponding voltage and current, okay.

They would induce a voltage and current between the two transmission lines and along the transmission line. They would then be directly proportional to the electric field. So, if the electric field is at plane wave, okay and magnetic field is also plane wave of the same, this one then the voltage and the currents are also plane waves, although we have never said that voltage and currents.

I mean, we said that voltage and currents are waves, but we never specify what kind of waves they are, okay. They are of course scalar waves because you are integrating and taking out the vector dependence over here, but the point is that electric and magnetic fields form a plane wave, which then induce a voltage and current, okay and we have been so far analyzing this voltage and the current, which comes from integral of H dot dl.

So, for the space between the transmission lines, this region actually supports a wave, which the solution of this wave equation if you describe that particular region by a wave equation will turn on to be plane waves, okay. And energy is actually carried not by the voltage or the current along the transmission line, but rather by this electric and magnetic fields, okay, by the Poynting theorem.

So, in fact, energy is not transmitted from one point to another point by the transmission line, although its name would suggest that, but rather the transmission line simply acts to guide the electric and magnetic fields in order to carry energy from one point to another point. So, in one very broad sense transmission lines are also guiding structures. These are the structures which guide electromagnetic energy in the form of electric and magnetic field from one point in space to other point in space.

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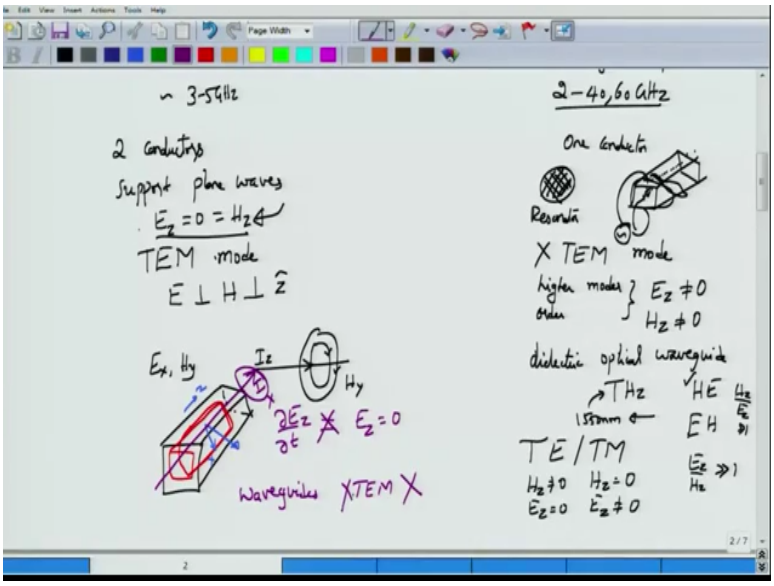

Okay, so if transmission lines are also waveguides, why do we have to study waveguides as the separate module? Why not we simply incorporate whatever we have studied in transmission lines and call that as waveguide theory? Well, there are many reasons for that one, some of the users will become apparent as we go along to the waveguide structure.

So, although we say transmission lines is actually guiding structure, the difference between the waveguide as traditionally understood and transmission line is this. Transmission lines in the form of coaxial cable to where PCB transmission line such as microstrip or strip line. They were only for up to a certain frequency, okay. Beyond that if you try to make them work they would offer significant loss and distortion, okay.

There are different cut off frequencies for each of these different transmission lines, so we do not have to get into that, but anywhere in the range of 3 to 5 gigahertz and above, certainly most of these transmission line structures would not really be guiding energy, okay. Whereas waveguides, okay, are structures which actually conduct very high frequency signal. So, they actually conduct signals around say from 2 to almost 40, 60 gigahertz, okay.

So, these waveguide structures are extensively used to guide really high frequency or microwave signals and therefore they are quite prevalent in microwave literature, okay. So, in microwave devices, you can see waveguides forming, I mean waveguides being used to guide energy flow. Even waveguides are guiding structure. But there have to be some difference between them apart from the frequency of operation, right and then a significant difference.

Transmission lines require at least two conductors and they support plane waves, okay. They support plane waves, which means that there is no corresponding E z assuming that the transmission line is along z and there is no H z. None of these two components exist for plane waves and these are the ones which are supported by the transmission line. In fact this plane wave structure is called I mean a transverse electromagnetic mode. Mode being just a sophisticated jargon for solution of Maxwell's equation.

So, you solve Maxwell's equation whatever the electric and magnetic field expressions that you get or the electric and magnetic field values that you get, those are called as modes, okay. And this particular, I mean plane waves are actually examples of what is called as transverse electromagnetic modes. Why do we call this transverse electromagnetic mode? I have described this in the wave module because electric field is perpendicular to magnetic field.

And both are perpendicular to the direction of wave propagation, whereas waveguides are made up only one conductor. Now, how can I make it of only one conductor? Can I just take one ball you know made out of metal and say this is a waveguide. Well, technically this does not become a waveguide, what it actually becomes is called as a resonator and we will study resonator sometime later.

But with one conductor, okay, for example, if you are able to make a box out of this conductor, right. Keep it hallow at both ends and then launch your voltage here, okay. So, you would launch voltage by actually connecting to the conducting plate some voltage source, this would create an electric field and magnetic field and this electric and magnetic fields are transported from one side to the load side, okay.

So, most waveguides at least the metallic waveguides that I am showing here would consist of only one conductor, okay. And this conductor, so why do we say one conductor because everything here is made up only one metal and there is one conducting continuous conductor out there, okay. So, made out of one conductor they do not support TEM mode, okay. There is a small reason why they do not so, we will discuss that when we really discuss waveguides, but most importantly they actually support higher order modes, okay.

Higher order modes simply mean that they have to be waves, but not of the same character as plane waves. The defining character of plane waves was that electric field was around. I mean the electric field and magnetic field, both did not have a component along the direction of the propagation, okay, that made it TEM mode solutions.

And plane waves also had this character that electric field E and magnetic field H in the transverse plane were independent of x and y directions, okay. So, you can have plane waves with some dependence of x and y, but the characteristic for TEM is that they should have z equal to zero and H z is equal to zero.

Whereas higher order modes are characterized by having at least one E z not equal to zero or H z not equal to zero or both, okay. So at least E z is should be non zero or H z should be non zero or both should be non zero. When do you actually get the situation of both to be non zero? You actually get that one in what is called a dielectric optical waveguides, okay. So, this is another class of waveguiding structures.

Here, energy is guided not in terms of gigahertz, energy is guided at terahertz. These are the corresponding frequencies for wavelengths, which are around say 1550 nanometer most popular band for optical communication. So, the corresponding frequencies are in terahertz, okay and they cannot use this metallic type of conductors to conduct, okay.

You do not actually take a metallic hallow tube and shine light from one side and then expect the light from other side. You do get that one, but that kind of a distance that is involved with typical optical waveguide such as an optical fibre, you won't be able to obtain from a conductor.

Moreover, the operating principles of dielectric optical waveguide is different from that of the metallic waveguides, okay. So, the point here is that waveguides would support higher order modes and this higher order modes depending on whether they do not have E z or do not have

H z are characterized as TE or TM. For TM, H z is equal to zero, but E z of course should not be zero. For TE, H z is not equal to zero, but E z is equal to zero, okay.

These cases where both E z and H z are present which acquiring dielectric optical waveguides are further characterized as H E or E H modes. In the H E modes, H is the one which is dominating that is even though H z is there, the ratio of H z to E z is much larger than one, okay. Whereas for the E H case the ratio of E z to H z is much larger than one. So, it means that E z is actually quite dominating the mode structure, okay.

So, we are going to study in the next module, we will start study of waveguides, but the lesson for this particular module, which introduces waveguides to you is that transmission lines are also waveguides. They also guide energy from one point to another point, but they are made out of at least two conductors because they are made out of two conductors, they do support TEM mode and peer transmission line modes are only TEM modes.

Waveguide would have one conductor and it would consist of, in a metallic case, it would consists of a hallow tube of metal, okay. The metal could have any cross section. It could have been rectangular cross section. It could be circular cross section. It could be a spherical cross section, okay. So, it can have a different cross section, but all of it has to be made out of only one conductor and they do not support TEM modes, but they do support higher order modes.

Now before finishing this module, let me just explain to you very briefly why these waveguides would not support TEM mode. Remember to support a TEM mode I need E x and H y. And how do I get H y? Only when I have one conductor, which is carrying current along the z direction, okay or equivalently having, so carrying the current along the z direction would - magnetic field lines around it, okay and these field lines would then be forming the magnetic fields along y direction, right.

If you space them apart, they would be forming the y direction, y directed magnetic field, okay, so, this is very important. For a waveguide okay, which is say rectangular waveguide, which I am assuming in this particular case. Rectangular waveguide does not have any conductor in between, right, so, that is obvious. It does not have any conductor, right. So, if I were to assume a region of space in between, okay.

So, if I assume a region of space in between, okay and you know it should more probably should be something like this. So, in the middle of the waveguide, if I assume and then say I want TEM mode, which means that electric field lines should drop from top conductor point to the bottom conductor although they are actually of the same conducting thing. But for the magnetic field to be along the H y direction, so this is along the z direction.

This is along the x direction. For the magnetic field lines to come out of this loop you know, you have this loop that is sitting over here and for the magnetic fields to form loops inside the region between the waveguides, you need to have a central conductor, right. So, a central conductor must be there which is carrying a current, so that the magnetic field lines can actually form a loop properly. But this is a waveguide. It has only one conductor.

So, there is no second conductor here. The moment you introduce the second conductor; these are not the traditional waveguides. Because of the absence of a central conductor, there is no way that you can actually have a magnetic field loop around in any region in between the waveguides, okay. If you do not have a conventional current, that is alright. You can still have the displacement current, so del E by del T, right.

So, you can have del E z by del T, but unfortunately that is also not possible because we have said that this is a plane wave structure, so z is actually equal to zero. So because there is no longitudinal current, you cannot have magnetic fields and because of this reason you cannot have only E x and H y components, which form the plane wave or which actually form the transverse electric mode structure.

Therefore, waveguides do not support at TEM mode, okay.