Basic Building Blocks of Microwave Engineering
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Lecture – 01
Concept of Mode

Welcome to this first lecture on the NPTEL course, on Basic Building Blocks of Microwave Engineering. Now, the theme of this first week lecture will be the mathematical model of Microwave Transmission, you know that, from the source the electromagnetic energy propagates. Now it propagates through various channels, and then, reaches its destination, or receiver or sink. Now will model first, this first part, the transmission, and when the theme, the first lecture today that will address is, concept of mode in Microwave Transmission. Myself, Amitabha Bhattacharya, here in E & ECE department IIT, Kharagpur; you can reach me in my email here.

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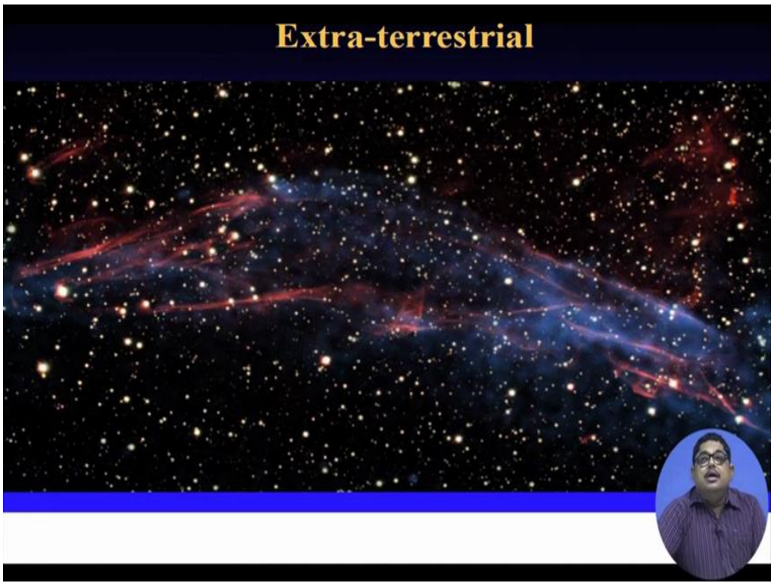

Now, let us see, if we will look at the universe, when we are, if you look beyond our, territory, that is earth, you see, we see so many stars, so many galaxies etcetera. Now do know, that, all of them, they radiate either light, that is why we are seeing them, or they are also radiating electromagnetic radiation, and there is one Nobel laureate Michel Boot, who measured, and found that in earth, everywhere, we have something like 2 degree Kelvin, of microwave radiation always, that the background microwave radiation. So, always we are getting bombarded with microwave radiation, we are living with it. Also you know, some emits solar flare, that is why when the solar flare reaches earth, it is not always, but sometimes when it reaches, solar flare is different from the normal light.

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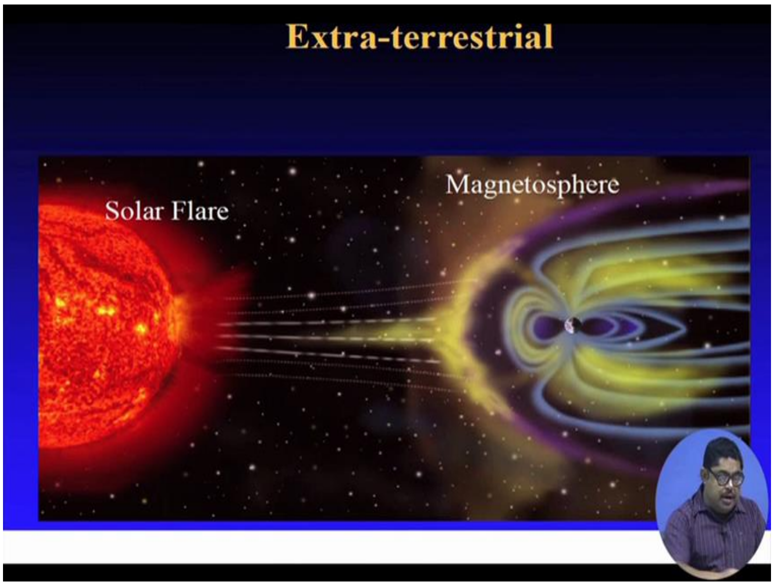

So, solar flare when it reaches, all the activities in communication etcetera, they get stopped. So, ISRO has a calendar, they keep track of when they solar flare reaches us, and that so they notify, and that time all our satellite etcetera, they stop working, because solar flare creates magnetosphere, and that creates huge magnetic, electromagnetic field.

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All of you are familiar with this side, in rainy season, you will see lightning. Now you see a lightning striking the earth, it is a huge source of electromagnetic emission, due to the high potential, high static charge potential, there is, air gets break down, and that is why, you see that, due to that break down the light gets produced, the sound gets produced.

Now, sound is not electromagnetic energy, but this light is, and that it reaches earth, it, you know, if you try to received this energy, you will get killed, but that energy comes here, when it is not striking, either a tree, or anything.

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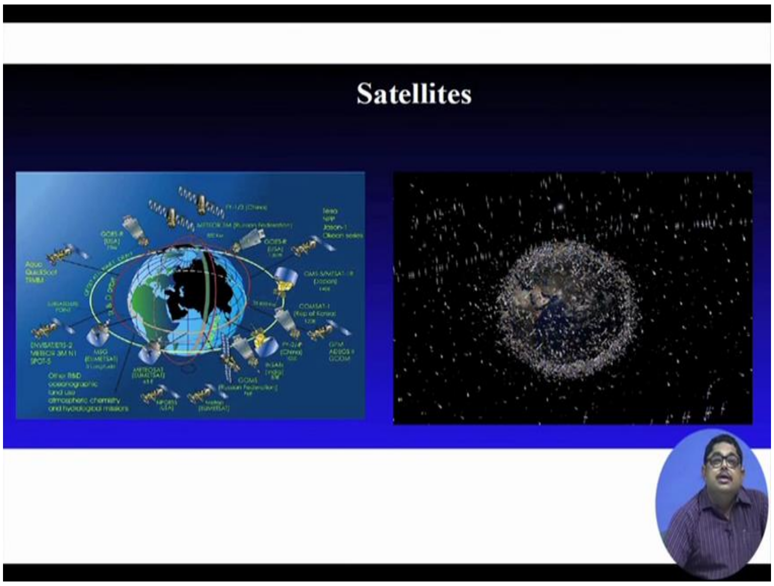

But, in the whole atmosphere, you are pervaded with these terrestrial lightings. Then you see satellites, natural satellites in the right side, in the left side the man made satellites, huge number of them, all of them or communicating with earth, by what, by electromagnetic signal. So, you are always getting signals from them.

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Then you see, let us see a typical family, how we are surviving today, there are Wi-Fi, that is emitting electromagnetic environment. You see satellite, that is doing that, you see TV, that is doing that, you see mobile phone, nothing but electromagnetic radiation, you see ground station, satellite ground station, you see your tab, or pager something, you see mobile phone, you see the electric towers, you see so many devices. So, we are living with it.

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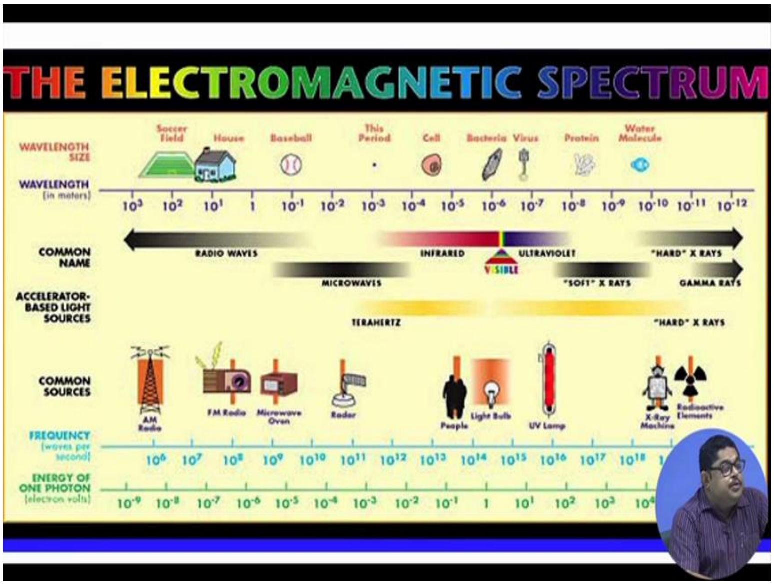

Now, we need to understand this environment, if we want to must have this technology. So, let us see that electromagnetic spectrum, you see, staring from the soccer field, that large size of wave length, to water molecule etcetera, all are electromagnetic environment. But we wont talk with this whole spectrum, our microwave technology means, you see, we have noted that, radio waves you can see, that up to the soccer field to up to the base ball size of wave length, base ball diameter wave length, that is radio waves, but after that, from base ball to let us say, this, a point dot, that wave length type of radiation, the radiation for which wave length is that long, that is denoted as microwave, as you can see, that, this is the zone of microwave. So, here we will mainly talk of that, and just beyond that, you see if, you go still further in wavelength; that means, still higher you know, frequency you can appropriately see from here, we are reaching terahertz variation.

Now, microwave radiation, as the technology is progressing day by day, it is going towards terahertz radiation, and similarly this, terahertz radiation also coming day by day, beyond, so, almost this 2 technologies are getting merged, or I think, when you people will be finishing your career, that time it will be completely merged.

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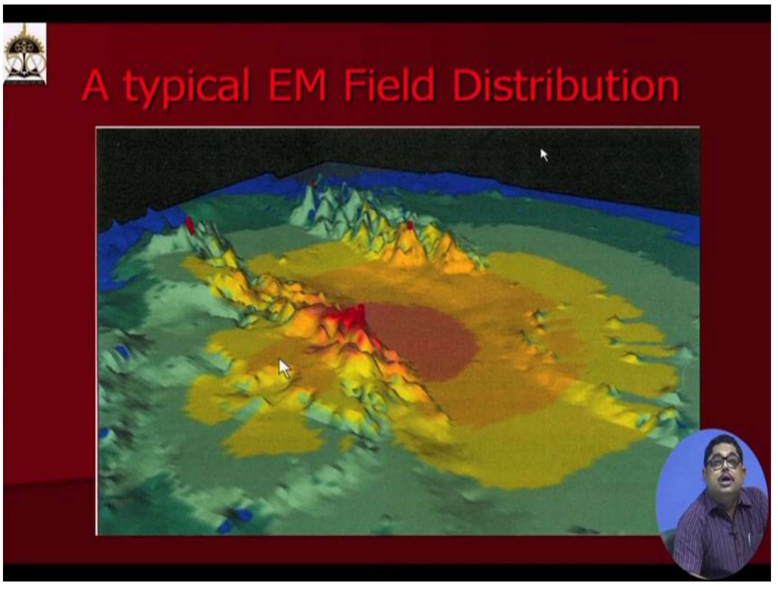

So, we need to understand this technology, and for that, this following lectures will help, you to understand the basics of that. Now you see, from all these field, if I look at any environment, actually we are doing in a particular place, we are trying to map the electromagnetic field distribution, and it came sometime like this, there is a color plot. So, you see the red ones, there the maximum things, maximum radiation that the electromagnetic radiation, then it is coming down, it is actually the radiation density, electric field radiation density, at that point.

And you see that gradually it is going down; obviously, this blue etcetera, those are very low, but you see there are various types of this, field distributions are possible.

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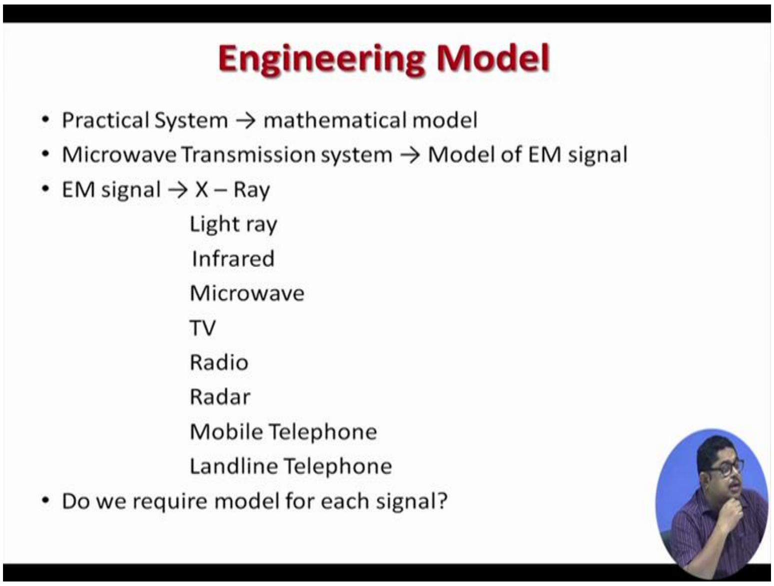

Now the question is, if you want to understand, and Microwave Engineering, then we needs a model, that is the basic task of any engineering, that when we try to analyze, or we try to understand something, we make a model. So, that is why we say that if you want to understand, you want to design, you want to analyze any practical system, you want a mathematical model. So, for Microwave Transmission system also, we want model of this EM signal. As I shown you, just before that, if I want to have what is happening, I need a model, mathematical model of EM signal. Now EM signal again, I have listed, for your convenience from that spectrum graph, that you know x ray, light ray, infrared microwave, TV, radio, radar, mobile telephone, landline telephone, everything comes under EM signal, out of that, I can say that, microwave, TV, then radar, then somewhat mobile telephone, these are in our microwave zone.

So, the question is, do we need for each of this type of signals, because each of signal will be different, that is why, there are co-existing at any place, all the signals are present.

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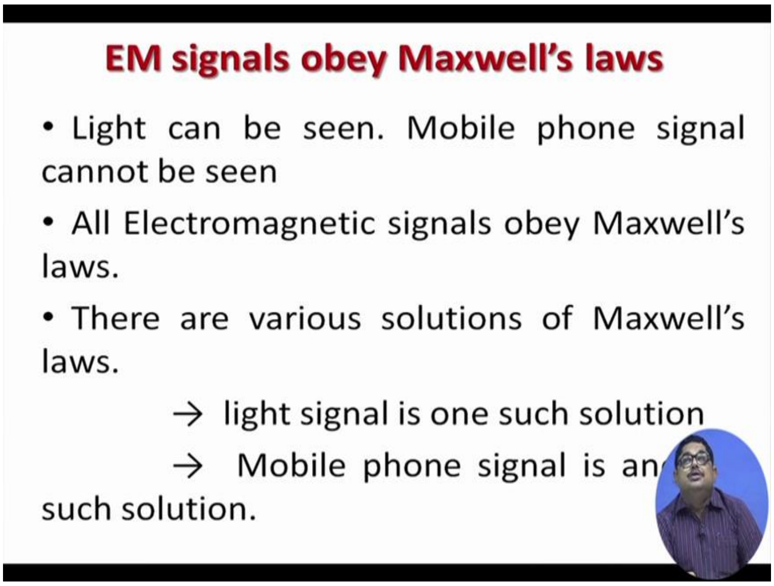

Now that means, if I want to understand, do I need a model for each of these signal? Then my job is just remembering all those models, it will be a huge task, fortunately it is not so. So, now, all these EM signals, they will be Maxwells laws. All EM signals, light, you know (Refer Time: 09:10) proved that, light is indeed a form of electromagnetic radiation. So, let us see, light and mobile phone signal, now both can be, see light can be seen, but mobile phone signal cannot be seen, but still both of them obeys Maxwells equation. There are various solutions of Maxwells laws, light signal is one such solution, mobile phone signal is another such solution, radar signal is another such solution, etcetera, etcetera.

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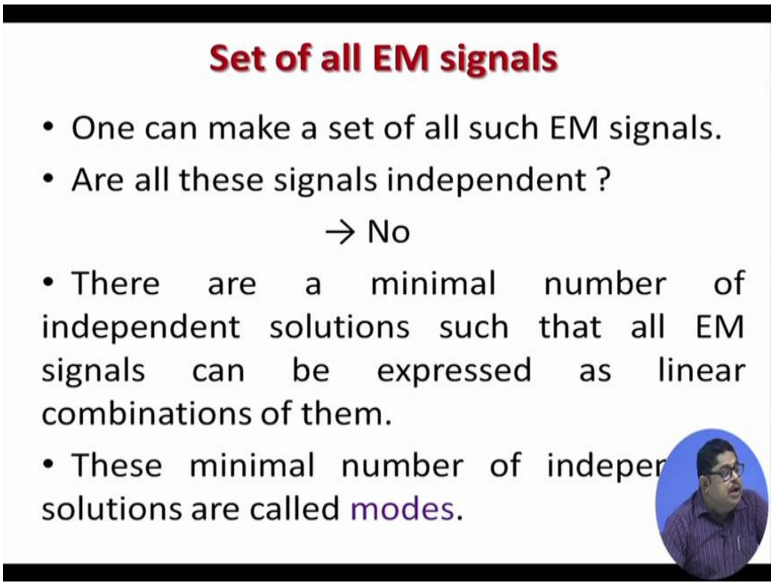

So, do I need to understand all these? So; that means, let us make a set of all EM signals. So, one can make a set of all such EM signals. are all these signals independent? If it was, then we had to understand all these signals, but no, answer is no, fortunate for us, there are a minimal number of independent solutions, such that, all EM signals cab be expressed as, linear combinations of them. So, we see that, though there are various solutions, but they are not independent, there is a minimal list of independent solutions, and all solutions are linear combinations of them. So, that we have fortunate, and these minimal number of independent solutions, are called modes. So, you see, that people generally say, that modes, what is a mode? Modes are solutions of Maxwell's equation. I say it is partly to answer because, any electromagnetic signal, as I said, that light signal, or a microwave signal, or a radar signal, that is also solution of electromagnetic signal.

But all signals are not called modes. Modes are the number of independent solutions, minimal number, in which we can express.

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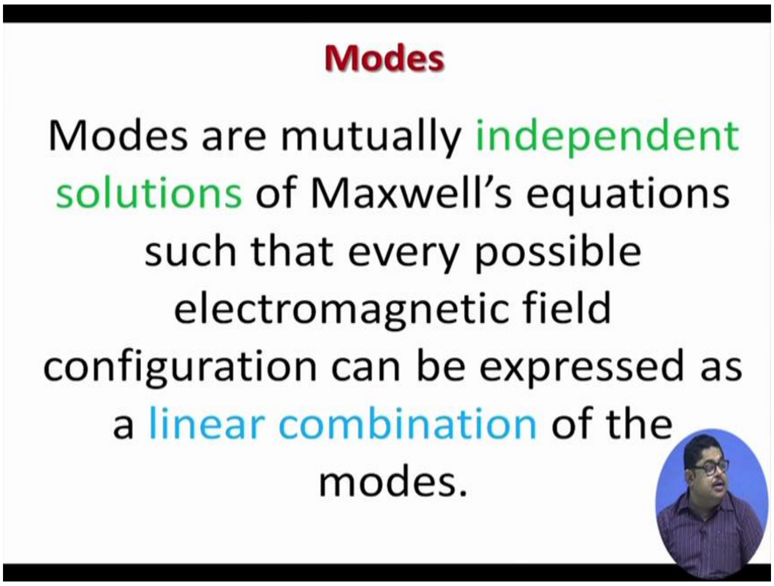

Now those who are familiar with set theory, they understand, that basically, this we can call as a basis set, you see, if I have a set of signals, then there is a minimal number of sets, minimal number of elements, of that set, in terms of which, I can express all the elements of that set, that set its called the basis set. Like for electric electrical signals, Fourier proved, the famous Fourier, by this Fourier theorem, he proved, that you can take a exponential basis set, to express all sorts of electrical signals. That is why, today we take, either cos or sin sinusoidal signal, and we analyze that and say, we know all the signals, because all the signals can be linearly expressed like that.

So, Fourier took a basis set. There is other basis set also possible. Now modes, its precise definition is, modes are mutually independent solutions, of Maxwell's equation, such that, every possible electromagnetic field configuration can be expressed as a linear combination of the modes. So, for our landing purpose, if I understand the field distribution in a mode, then I can construct any signal.

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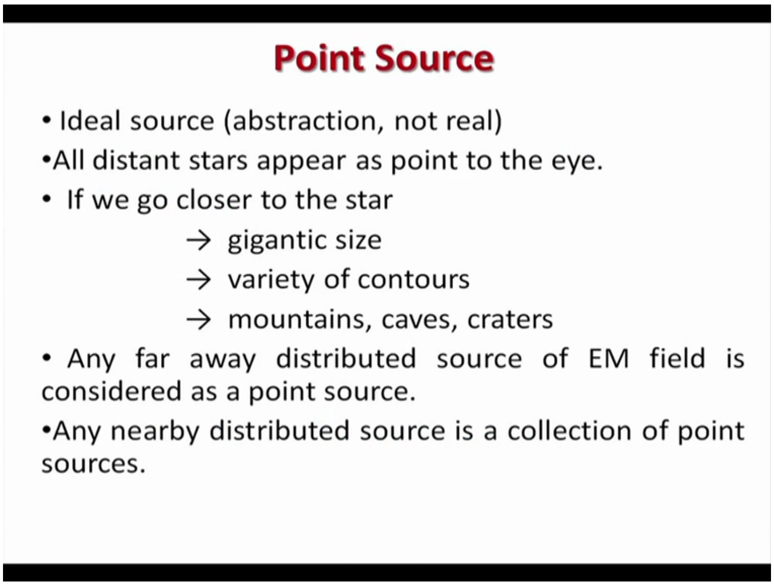

So, my model requires that, what will be the, these modes field distribution. So, let us come; obviously, when EM signal is produced, there needs to be a source, that source may be near the signal, because electromagnetic signal propagates as a wave. So, when I am looking at the signal, the source may be near, may be far away, but to start with, one kind of source, is a point source.

Now, point source is actually an ideal source, like the concept of point in geometry, which you know, that it is an abstraction. Similarly ideal point source, its an ideal source, its an abstraction, no real source is a point source, all distant stars, as I showing in the first slide, that you see so many stars, but, they appear to be us as a somewhat, not point something more, but if you are really far away, then all distance stars appear as point to our eyes, but if we go closer to the star, what we see, we see the star, its a huge size, there are variety of contours, there are mountains here, there are rivers here, there are caves here, craters here, etcetera, etcetera. So, any far away distributed source of EM field is considered as a point source. And if the source is nearby, then we know, what is its contour. So, we can say that, it is summation of all those point source.

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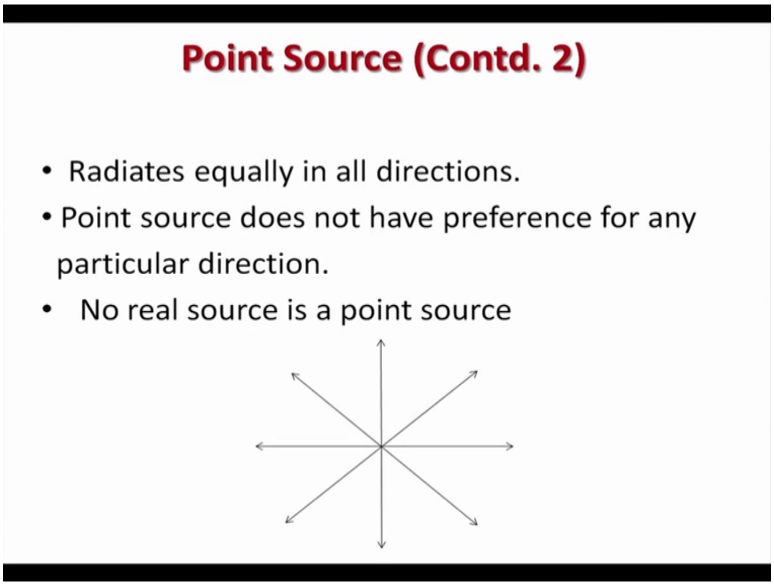

So, any distributed source nearby, we call it is summation of point source. Now point source, it radiates equally in all direction. This point, it does not have any preference, of radiation to any particular direction, again I am remind you, that no real source is a point source. Every real source, has a preferred wave of radiating, a preferred direction in which it radius more, than others, but when we idealize, or when we (Refer time: 14:58) point source we defined as, which radiates equally in all directions.

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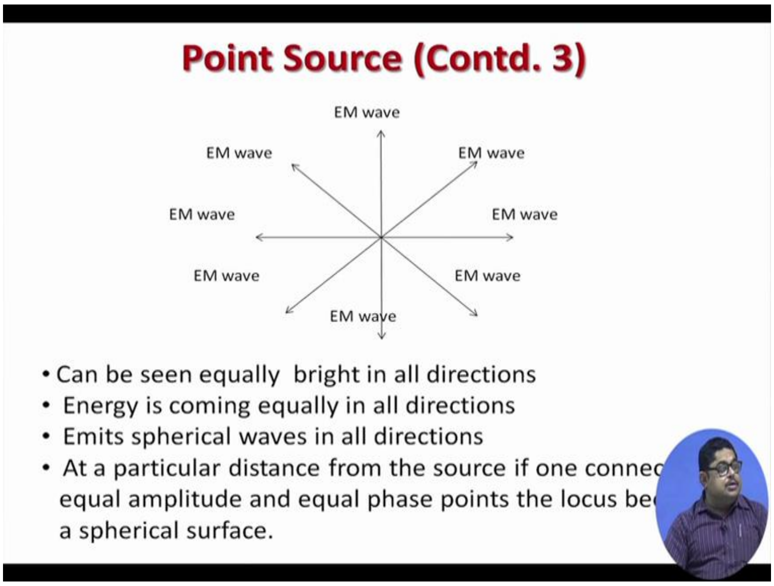

So, these; that means, that has, origin there is a point source. So, in all possible directions you are giving a wave can be seen equally bright in all directions. You have not seen anything till now, which does like that, but ideally we can say, because if you observed a distant star, now in the earth if you move reasonable distance, suppose in a region etcetera, you do not think that there is any change in that; that means, that is, to you to it is appearing is a point source.

But if you really travel far, then you are travelling much. So, something, suppose from northern hemisphere to southern hemisphere, if you come then you see that, that is changing. So, we can say that energy is coming equally, in all direction, from point source, and, people have found out the solutions for that, if it has been seen that emits spherical waves in all directions. So, if you are center of a sphere, then the energy is equally going along larger and larger spheres, and coming to you. At a particular distance from the source, if we connect, all the equal amplitude and equal phase point, that mean whose, any field electric field, or magnetic field, is equal amplitude and equal phase points if you connect, then the locus become a spherical surface.

So, its phase front is call spherical so; that means, when elect any, any point source is emits electromagnetic signal, then, at a particular distance, if we connect all the equal amplitude and equal phase; that means, equal signals, where they are then if you connect that that becomes a spherical surface.

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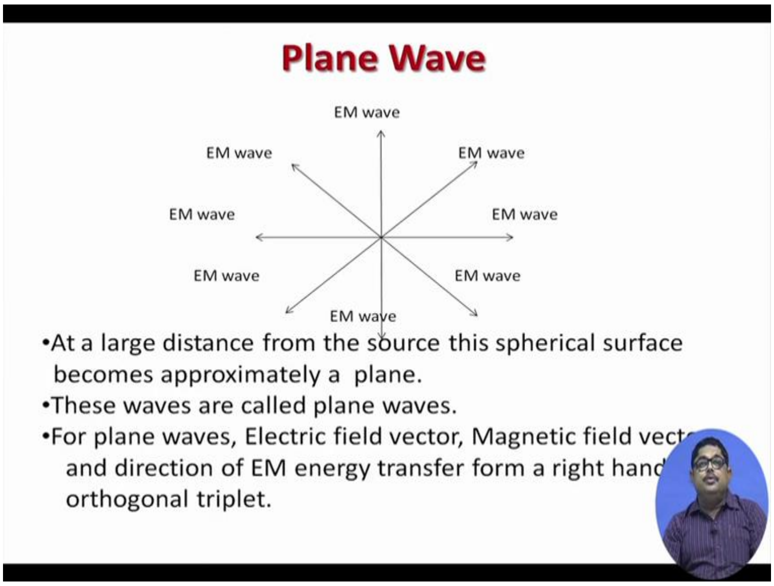

That is why we say, that point source emits, spherical waves, in all directions. Now at a large distance from the source, you know that, sphere, if you go and constructing larger and larger spheres, now, very large sphere, at a particular place you will see, that the spherical surface is almost becoming a planer surface. So, that is why, we are saying that at a large distance from the source, this spherical surface becomes appropriately a plane, then, these waves are called plane waves.

Now, will see plane waves, and or we have already seen plane waves in EM theory. Plane waves means, in that plane, there are electric field vector, magnetic field vector, they do not have any variation, there constant over the plane, that is called uniform plane wave. First plane wave, that all equal amplitude and equal phase points, they are plane, and then if you have uniform plane wave, which is the variety of plane wave, where they will have, the there is no variation in that plane, of the amplitude, or phase of that thing. So, that plane waves, you have seen already, it solution we have seen in thing, it is that, cos omega t, minus k z type of thing, e to the power minus z k z, that thing. So, for plane waves, you have all also seen, that, electric field vector, magnetic field vector, and direction of EM energy, propagation of EM energy, direction, that form a right handed orthogonal triplet, these you have already seen.

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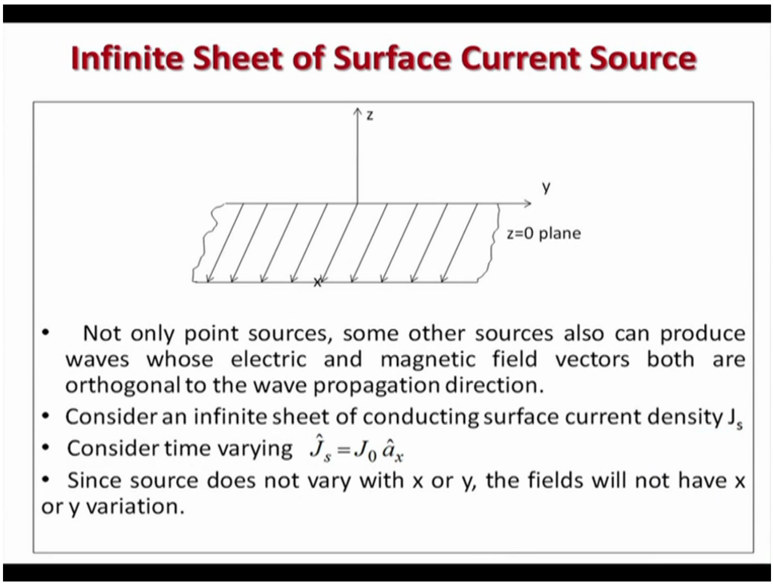

So, for plane waves this is true. Now, we see the second type of, or another type of source, instead of point source, suppose we have, all these are abstractions, but it will help you to understand what is the source, and how it radiates. Suppose we have, an infinite sheet of, surface current source; that means, a whole plane, where we have, a one directed surface current, it is call sheet of surface source. So, here we have taken that, in the, z is equal to zero plane, the sheet of surface current source is (Refer Time: 19:18) So, what we have written that, not only point sources, some other sources also can produce waves whose electric and magnetic field, field vectors, both are orthogonal to the wave propagation direction.

So, consider an infinite sheet of conducting surface, current density, let us call that, surface current density, J s and consider; obviously, since we have talking of electromagnetic field; that means, this is not a DC current, it is an AC current, that is why I am writing considered time varying j s, the surface current density is time varying, it has a time function it is depend function of t, and also, for simplicity I have assumed that it is in the x y plane, it is x directed. It can lie in any direction, but we can orient our, x y thing. So, that for a simplicity, it comes x directed thing.

Now, since you see the source, these source, it is an infinite source, though my drawing does not represent that, but in x y plane, it has an infinite variation. Actually there is an x, here you see, this is x, though I do not think it has mixed with the contour. So, in x y plane, it is infinite. So, since it is infinite, and you know, that if there is an electric, there is a conduction current; that means, in that direction there are, the electric field also. So, it j s is in a x direction; obviously, the electric field will also be in the x direction, but since there is no variation in the whole infinite plane, in either x or y, please remember that it may be x directed, the current is x directed electric field is also x directed, but they do not have any variation, because the whole source does not have any variation, in the neither x or y direction.

But if definitely has a variation in the z direction, because suddenly it is here, just as z is equal to 0 minus, it is not there at z is equal to 0 plus it is not there. So, it has a variation only in the z direction, but in x or y direction, it does not have any variation.

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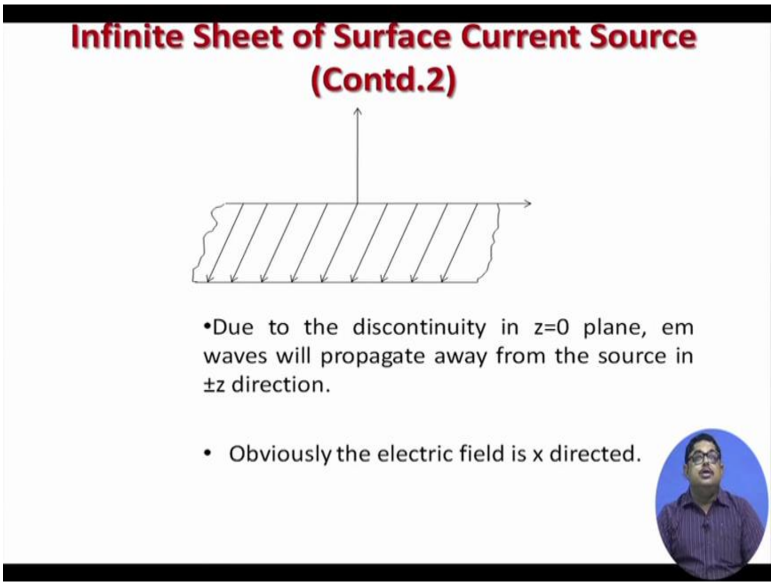

So, this type of source, due to the discontinuity as was saying in the z is equal to zero plane, there will be EM waves propagating away, from the source in plus minus z direction. This, we will always remember, that if there is any source has a discontinuity, that it is suddenly there, and then not there, then it will radiates. So, it will radiate; obviously, in plus minus z direction, and already we have discussed that the electric field is x directed, the movement electric, the propagation of wave, or propagation of energy is in z direction.

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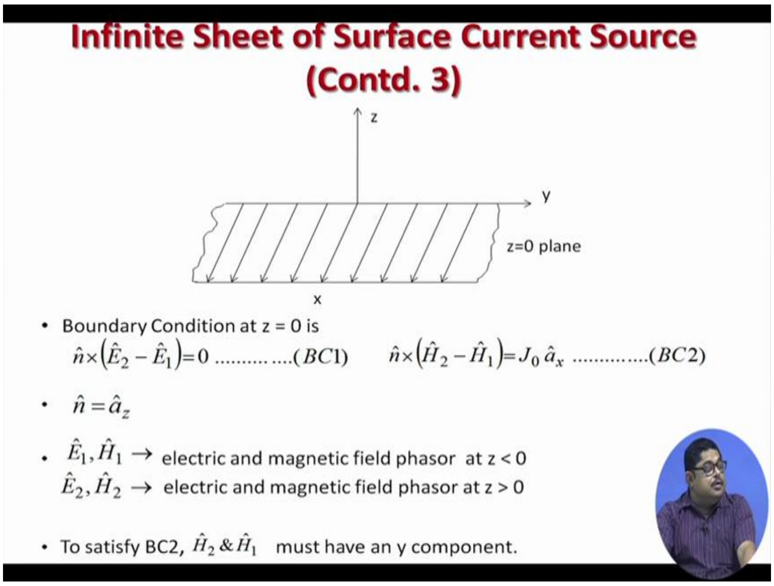

Now, let us put the, you all know boundary conditions of electromagnetic fields. So, boundary condition at z is equal to zero, if we apply, we know that, what this is saying, you know n is a normal vector. So, n cross e 2 minus e 1; that means, what tangential component should be continuous, tangential component of the electric field, should be continuous, that is the boundary condition one, of electromagnetic field. Similarly, the tangential component of magnetic field, n cross h 2 minus h 1 that is discontinuous and the amount of discontinuity is the surface current density. It is the second boundary condition of electromagnetic field, in our particular case, n is the outward normal. So, n is positive a z directed, and e 1, h 1, we are calling, it is the electric and magnetic field in region one, region one we are defining as, z less than zero; that means, below the current sheet, and z greater than zero is above the current sheet, where the fields are e 2, h 2, that is why we have written this boundary condition.

Now, to satisfy this boundary condition n is a z. So, a z cross e 2 minus e 2, we know that, e 2 minus e 1 will come, then the h 2 minus h 2. So, a z cross these, is equal to some a x component so; obviously, it says that, h 2 and h y, they must have y component, simple mathematics.

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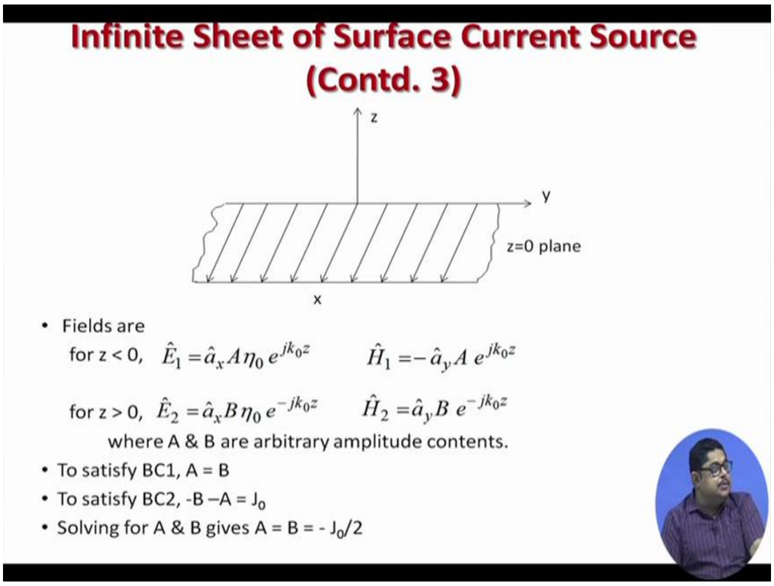

So, we can write the fields as E 1 (Refer Time: 24:18) that will be equal to, in a x directed, and then we assume some amplitude a, first we assume, since h one is y directed. So, H 1, let us assume, in the lower one, you see, to satisfy that equation, lower one it will be minus. So, minus a y, a is some amplitude, then we know that the field is propagating in z direction, means, its variation will be e to the power j k naught z, and E 1 and H 1, we know, that always they are related by the wave impedance, in free space it is propagating eta naught, by intrinsic impedance of free space. So, they, e one will be like this.

Similarly, at z greater than 0, we can write H 2 and E 2m some other constant, b amplitude, and some other constant, b here. So, a b needs to be found out. So, to satisfy boundary condition one, we get a is equal b to satisfy boundary condition two, you get this. So, solving we get that a and b, their values we get. So, by that, we can find out, that there is an electromagnetic field. So, we see that it also produces the surface current, infinite surface current, that produces and electric field, so that you can have, the propagation in the plus minus z direction.

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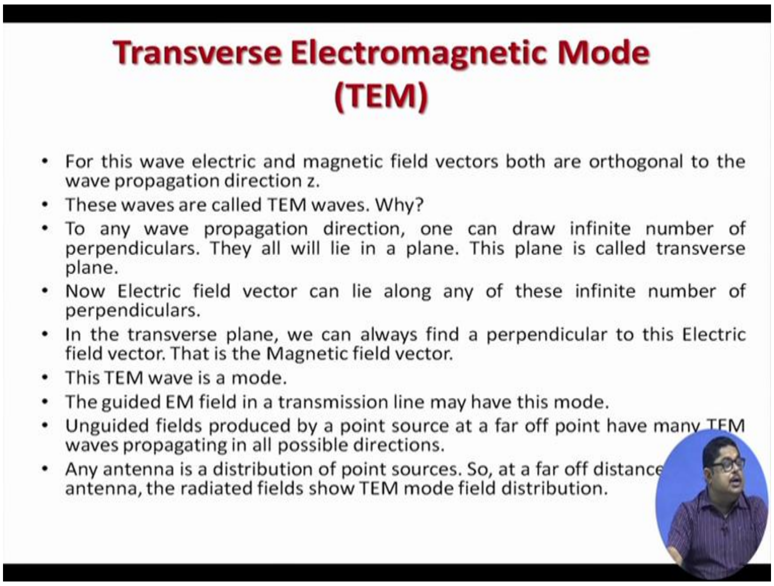

Now, so, in this case also, you see that we have, electric and magnetic field vectors, both are orthogonal to the wave propagation direction z. So, you see that, e and h, they are all lying in x y plane, the wave is going in z direction, the e and h will does not have any component in the propagation direction. This is the first mode that we introduced, that if and both the electric and magnetic field, they are lying on the transverse plane; that means, transverse to the direction of propagation, then we call that has TEM mode, or transverse electromagnetic modes, to any propagation direction, one can draw infinite number of perpendiculars; that means, if you have any direction to that, you can draw a perpendicular, draw perpendicular.

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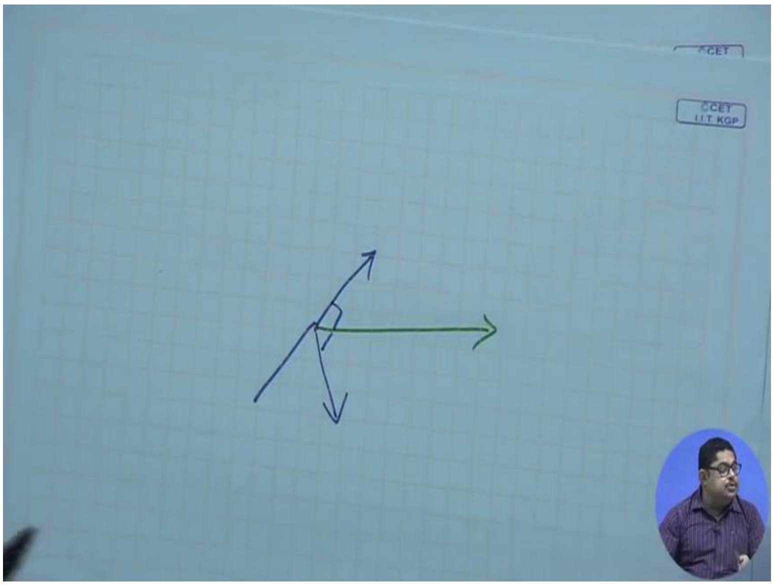

So, all these are perpendiculars, to it, you can have many, because with these I can have these as a perpendicular, with that I can have other perpendiculars also.

So, but all these perpendiculars, they will lie a plane, that is in this transverse plane, this plane. So, there any line is perpendicular, and now electric field vector can lie along any of these infinite number of perpendiculars. Now in the transverse plane, we can always find, in a plane we can find always a couple, another perpendicular, two perpendicular couple we can always locate. So, along the perpendicular to the electric plane, we can always locate another perpendicular, which is a magnetic field vector. So, these TEM wave is a mode. In a guided structure, like in normal (Refer Time: 27:58) transmission line, this mode propagates, in unguided fields; that means, when we radiate by antennas, then at a far off distance, from the antenna, this is becomes a TEM wave, that we have discussed that, from that stars, when we are far away, they becomes plane waves plane waves are an example of TEM mode but, reverse is not true, apart from plane waves also, there are many examples of TEM wave field distribution.

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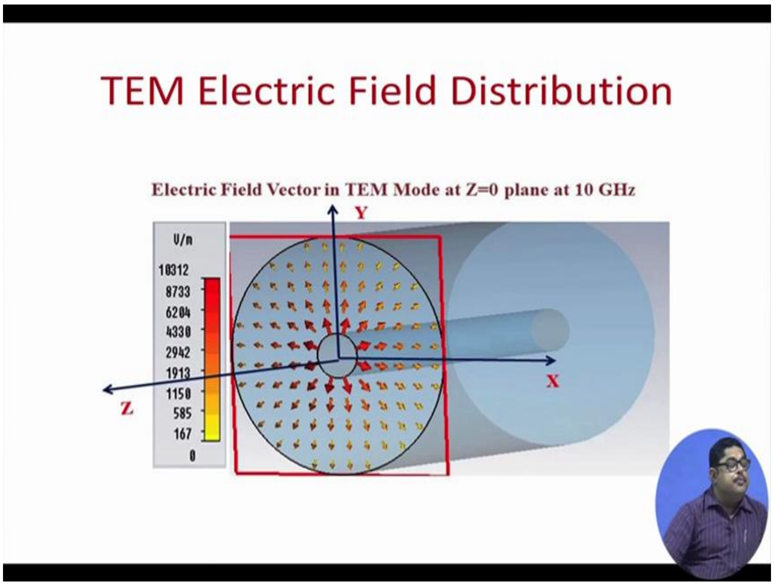

So, any antenna is a distribution of point sources, where at a far off distance from the antenna, the radiated fields show TEM mode field distribution. This is the TEM mode field distribution you see, that it is in a coaxial line, we get this type of distribution, here you see that we have so many, all the elec, this only one electric field I am showing, it is entirely in the x y plane, the propagation is taking place in the z direction.

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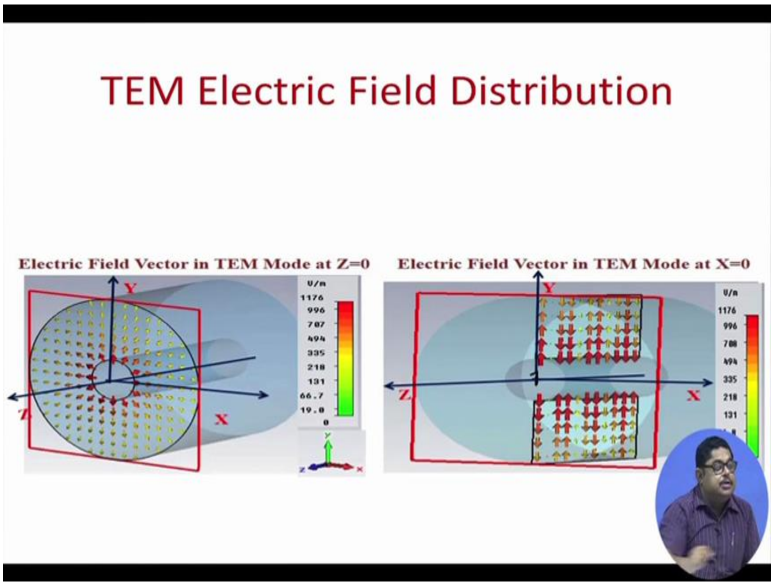

So, it is the magnitude is changing as you see from the color plot, but it is changing. So, you see if we look in the z direction, this is z direction the in a transverse plane, there is no z component. So, this is an example of a TEM field distribution.

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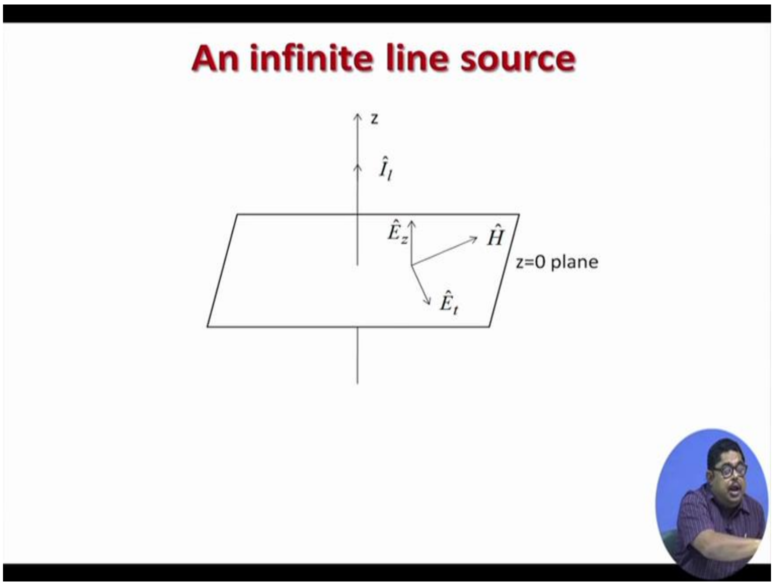

Now, let us see an infinite line source. So, this z directed line source, a, instead of infinite sheet of current, which produces TEM waves, we are now seeing an infinite line source. So, the source is a line infinite line I L, let us call.

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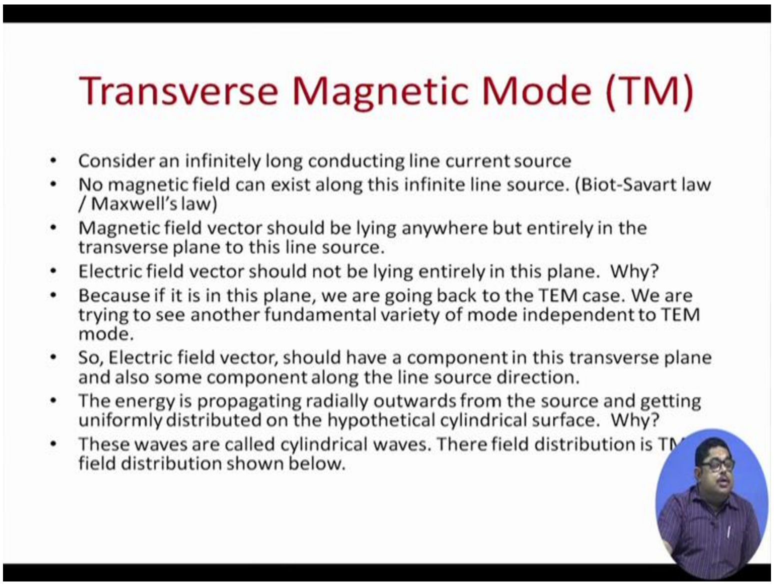

Now in the z plane, will be the transverse plane to this. Consider an infinitely long conducting line current source, no magnetic field can exist along this infinite line source, that is Biot Savart law, or Maxwells law. That you, if you have a current source, magnetic field is always perpendicular to the; that means, in the along this line source, there is no magnetic field component. So, where is the magnetic field vector then, it should lie along the transverse plane; that means, that z is equal to zero plane. So, magnetic field should lie there, now electric field vector, can be anything, but, you have already seen TEM case.

So, we say that, they are both the electric field vector, and magnetic field, field vector was in the perpendicular plane. Here we say that since we are trying to see, whether another mode is possible, and another solution of Maxwells equation, in another independent solution is possible. So, that is why we are checking that electric field vector should not be lying entirely in this plane, because if it lies entirely in this plane, that is the TEM case. So, if it is in this plane, we are going back to the TEM case. So, we have trying to say another fundamental variety of mode.

So, electric field vector should have a component, in this transverse plane, as well as some component along the line source direction. So, this mode is called transverse magnetic; that means, magnetic field is entirely in a plane, and if you do the mathematics, this line source gives that TEM mode. It does not give any TEM mode. The energy is propagating, how energy is propagating? If you consider, that considering that line current has an axis, if you consider a cylinder, throughout that cylinder surface, the energy is propagating. These waves are called cylindrical waves.

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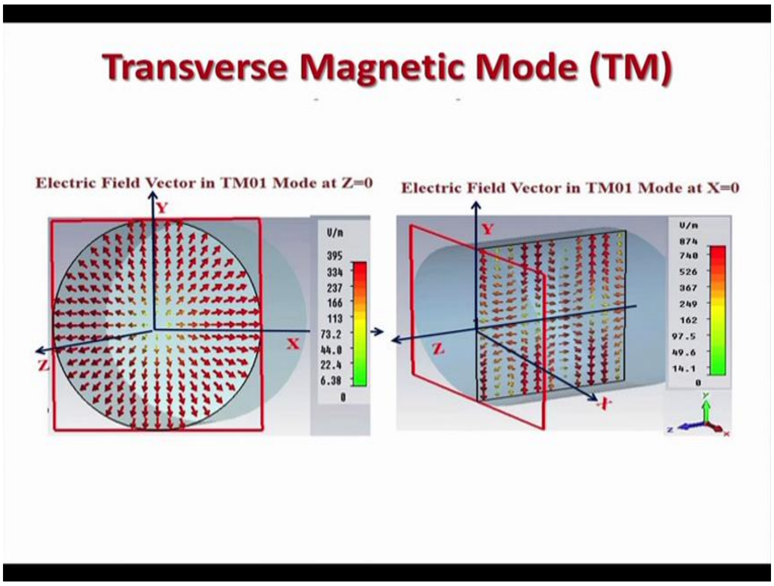

Their field distribution is TEM field distribution, this is a TEM field distribution, this comes in, we will see later, in circular type of (Refer Time: 31:46) guides, not coaxial cable; that means; only one conductor is here. So, in a hollow metallic pipe, cylindrical pipe, you see electric field vector, it is like this, also electric field vector, we are showing in the any between thing, at x is equal 0, it has a longitudinal component. This is an example of a transverse magnetic mode.

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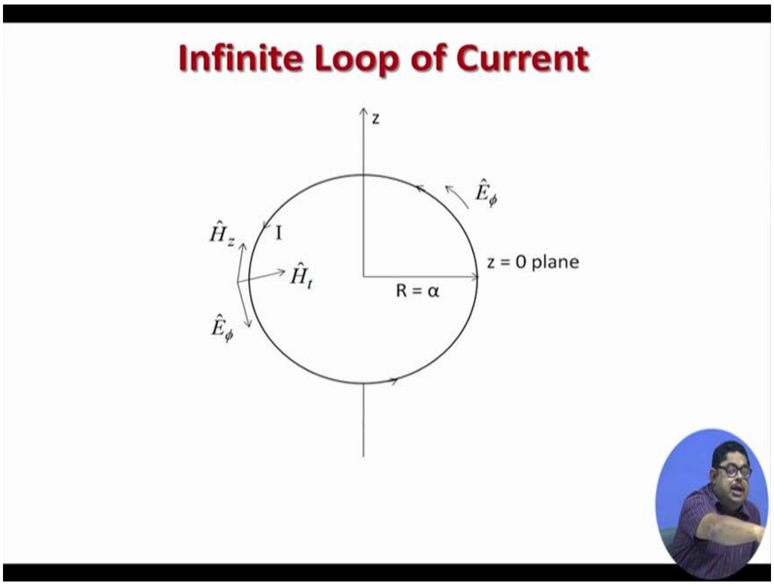

Now consider another example, that instead of that line source, let us make a loop, infinite loop of current, current carrying I. So, consider an infinite loop.

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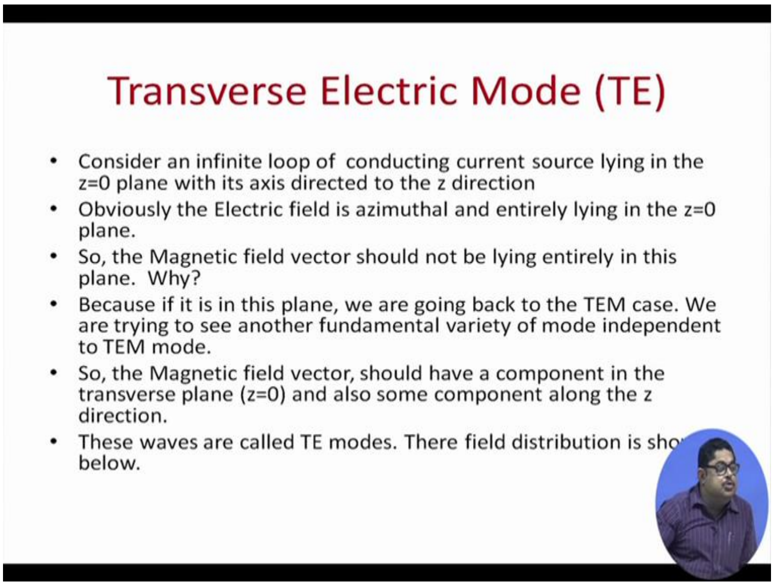

Obviously, the electric field will be azimuthal, you see at every point electric field is, because it should be in the direction of this conduction current, there is a conduction current here. So, it is in the e 5 direction, that is called azimuthal, and entirely lying in the z 0 plane, you see here, e 5, all are lying in the z is equal to 0 plane.

So, the magnetic field vector should not be lying entirely in this plane, why, because then we are going back to the TEM case, again that same logic. So, magnetic will should have a component in the transverse plane, and also some component along the z direction. These waves are called TE Modes their field distribution is like this. This come, we will see, in wave guides.

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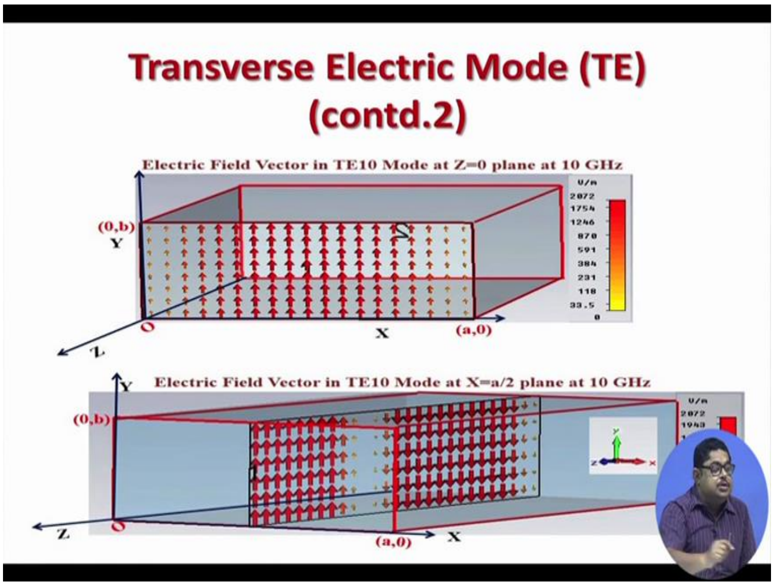

You are familiar with that, that it is a example of a TE 1, 0 mode, this type of various modes, but all of them, they have that you see in the transverse plane, the electric field is lying, we are seeing in a longitudinal plane, you see it is basically the wave guide. between that, if we can see, will see that field distribution will like this, there is no component which is in the z direction.

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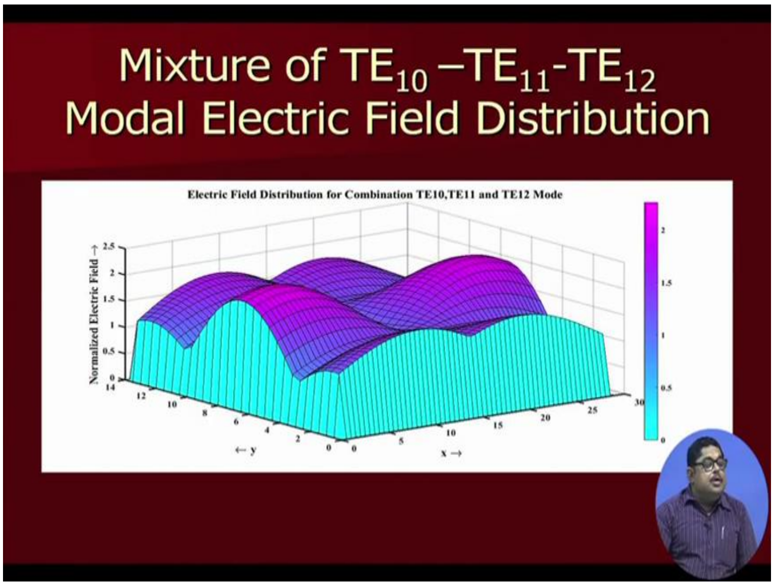

So, electric field is entirely in the transverse direction, and as I was saying that, with mixing these type of various modes, you see three TEM t type of electric field distribution, if they are mixed, then you get a field distribution like this.

So, all these various things, but all are linear combinations of these modes. So, a particular field may be, suppose when in a coaxial line, transmission line, you can have all the modes possible, TEM, TE, TM, all the them can be possible. In wave guides, you cannot have TEM, and so, if you see the actual field distribution, you will see something haphazard, but if you break it into this components, you will then understand, that how much of T, how much of TEM, and which type of T also have various with numbers, this two numbers, they are giving two dimensional modes. So, various numbers are possible. So, with that you get all the real life signals.

So, if you understand modes, you can easily a break the fields in to these modes, and then your analysis will precede. So, that was our first lecture, that what is the concept of mode. I think I have tried to make you understand, that there are 3 fundamental modes, TEM, TE and T0, and where from they come, have given you examples, that which type of sources can produce a pure of that variety. In real life, you have a source which is mixture, of all these various sources I have shown. So, with that they produce various types of TEM, TE, and T0. Now we need a supporting structure which can carry that. So, that energy will be coming from transmitted to receiver that will see, one by one in the next lecture.

Thank you.