Transmission Lines and E.M. Waves
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Lecture-48

Welcome, in previous lectures we developed the theoretical foundation of antennas specifically we investigated characteristics of the basic current element called the Hertz Dipole and then using the information which you got from the Hertz Dipole we analyze the radiation characteristics of a dipole and then we saw as the length of the dipole varies the radiation pattern which is one of the crucial characteristics of an antenna it varies and depending upon the length of the antenna you have multiple lobes or multiple beams that means multiple directions in which the radiation goes . We also saw that as the length of the antenna increases then there are certain directions in which there is no radiation apart from the principle nulls which are along the dipole there are some other directions also in which there is no radiation or there is no electric and magnetic field then we can say that if you have a general antenna a general antenna has a direction in which the maximum power then there are certain directions in which no power goes and there may be some other directions in which again you are having a local maxima that means if you go in the neighborhood of the direction power is maximum at that direction but it is not the absolute maximum if you see the three dimensional space as a hope.

So today we will try to investigate the general characteristics of antenna which will also be applicable to Hertz Dipole and the Linear Dipole but here we will essentially try to characterize the radiation patterns of a antenna. This is important when you have different kinds of antenna normally we require some comparison mechanism that is the mechanism by which the two different antennas can be prepared, at the moment we have radiation pattern which is a very elaborate description which is a three dimensional surface and it is very difficult to compare one antenna with respect to other quantitatively, looking at the radiation pattern we can always say this antenna has certain direction for maximum radiation or certain direction for nulls but what we are looking for is some quantitative measure on the basis of which antennas can be compared and that is what essentially we discuss in today's lecture we will discuss the general radiation characteristics of an antenna.

So let us look how the general radiation pattern would look like. As we saw the radiation pattern is the variation of the electric field magnitude as the function of θ and ø. Let us say if I take any plane then the radiation pattern in general would look something like that here I have drawn the magnitude of electric field as a function of angle and this angle I am measuring in the plane of the paper. So this is the direction in which you have maximum electric field that means you get maximum power then there are these directions in which there is no electric field no power goes in this and as we saw earlier for the dipole we call these directions as nulls so we have null here, we have null here, we have null here, here and here.

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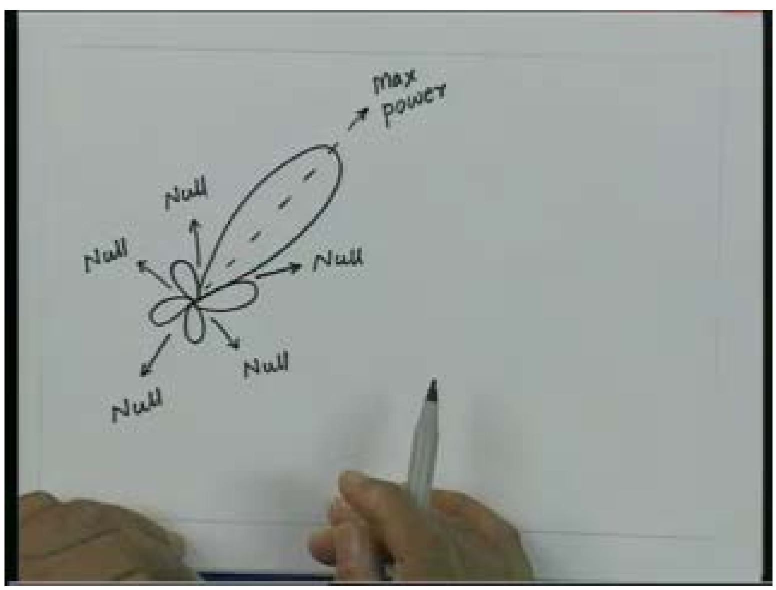

In this particular radiation pattern we have the direction in which the maximum power goes and there will be five directions in which no power goes the electric field is zero in this direction. Then if I go in this direction between these two nulls where the electric field is locally maximum so if I measure the magnetic field the magnitude of the electric field here it is higher compared to the neighboring points same is here same is here same is here but this maximum current is much smaller compared to this amplitude which is really the absolute maxima which you see in the radiation pattern.

So this direction in which there is absolute direction we call that as the main beam of your radiation pattern or main beam of the antenna so we call this lobe or this angular region where the maximum power is going as the main beam of the antenna and then all this minor lobes which you have seen the angular zones in which your power goes again there is a local maximum but this is much smaller compared to this all this are called the side lobes of the radiation pattern so all this small ones are called the side lobes of the radiation pattern. So in this case we have four side lobes and we have one direction of the main beam.

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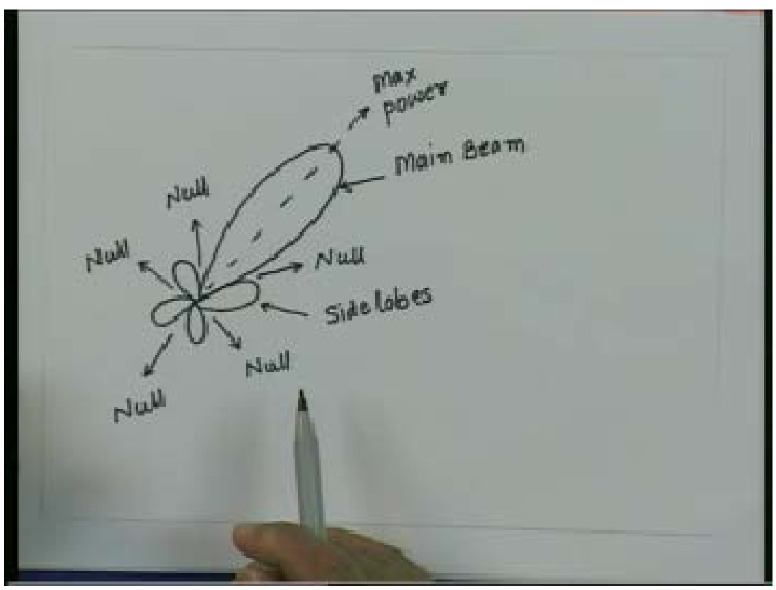

Now as we saw last time depending upon the application you may require a very directional antenna in the sense I want to send the power only in a particular direction as we saw let us say in microwave power so in that case I want these quantities the side lobes should be as small as possible and most of the field must get concentrated only in direction of the main beam or the maximum power direction, whereas if I want to use the antenna for broadcasting application then this beam should be as wide as possible and therefore there should not be these zones where the nulls are there.

So I have depending upon the application variety of requirements for radiation pattern in some case I will require narrow beam in other case I might require a very wide beam and no nulls so as broadcasting applications the nulls are not designable because in those sectors there will not be any radiation and there will not be any reception of the electromagnetic wave. Many times the same radiation pattern is drawn in a Cartesian way that means if I measure the angle and plot this angle like a Cartesian coordinate θ so let us say this angle θ was some distance direction which I had here and I measure all my angles like that as θ.

Now I can plot from θ which is $\theta = 0$ I have taken some reference direction this is zero, the maximum beam will be in direction may be some thirty forty degrees then you are having a null which is somewhere around zero and you are having side loop so the pattern would look something like that and so on where this thing corresponds to the main beam of your antenna this null would correspond to this null, this null would correspond to this null, this null would correspond to that so if I say this is null 1, this is null 2, this is null 3, this is null 4 and this is null 5, this is the main beam and let us say this angle of the direction of the main beam angle is denoted by θ_0 so this angle will be θ_0 then this will be null 5 so this direction is 5, this direction will be null 1, this will be null 2 this will be null 4 and so on.

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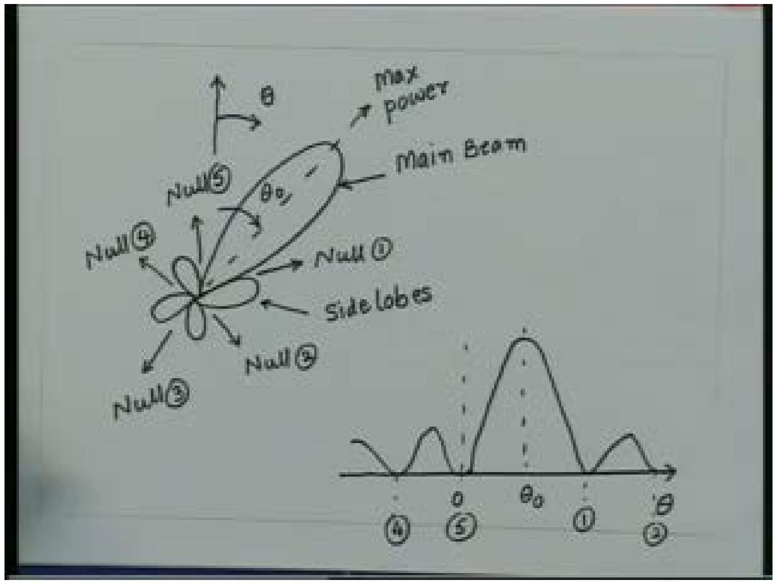

So essentially we can take the radiation pattern which is actually a polar plot in a plane as a Cartesian plot where the angle is plotted on the x axis and the amplitude of the electric field is plotted on the wires so this is I am plotting here |E|, both type of patterns are seen in literature some people prefer to draw the radiation pattern like this sometime when you want to do more calculations may be drawing the radiation pattern like this comes out to be more handy.

Now if I look at this radiation pattern there are certain characteristic parameters I can extract from this radiation pattern and the first thing immediately comes to your mind is the direction of the main beam so different antennas can be sort of compared on the basis of direction of their main beam so we have parameter the direction of the main beam θ_0 so normally when we compare the radiation pattern we define certain reference direction and with respect to this direction essentially we give the direction of the maximum radiation here I have written θ_0 but in general it is a three dimensional this will be θ_0 ϕ_0 because this beam will be inclined in the phi plane.

So in general you can say the direction of the main beam (θ_0, ϕ_0) in the angular coordinates the second thing which you can see from this radiation pattern and that is what is the angular sector over which the beam is illuminating the region. So there are various possibilities one is if I go to the nulls the radiation goes to zero so effectively I have an angular sector which is decided by these two nulls over which the power is going in the main beam but then you will note that when I go very far away from the beam go towards the null we are having a variation of the electric field from maximum to zero towards the centre.

Normally in the electrical engineering we define a quantity called the effective width that means that is the region over which the power lies fifty percent of its maximum value since power density is proportional to the square of the electric field and this is the plot of the electric field the electric field if it lies within one over root two o its maximum value the power will lie within fifty percent of its maximum value. So what we do is we can define the two directions where the electric field drops to one over root two of its maximum value. So let us say since the radiation pattern is normalized this value is one and this value is one then I go to these two angles one is here and here which correspond to this two angles where the electric field is dropped to one upon root two. So I have got this two directions let us say θ_1 and θ_2 on either side of the maximum of the main beam where the electric field would drop to one over root two of its maximum value, these thing can be called as the three dB points on the radiation pattern because at this points the radiation of the power density would drop to fifty percent of its maximum value.

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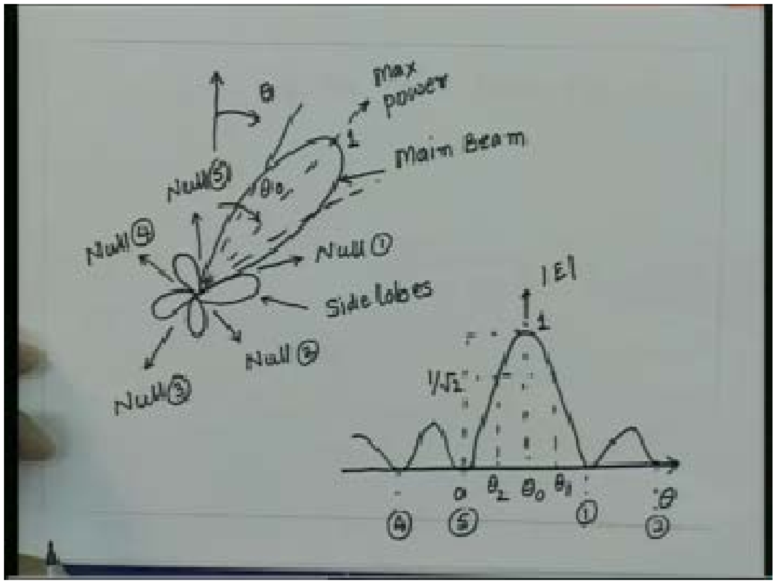

Then one can say if fifty percent variation of the power density is acceptable we can say effectively that is the angular sector over which your antenna beam is illuminating the region the power is going effectively over this sector. So we define this beam width $\theta_1 - \theta_2$ as the half power beam width of the antenna and that is the effective width over which the antenna is sending power along the main beam. So we have a second parameter called half power beam width.

Again we can define the half power beam width in various planes because the region which you are considering it may not be a circular kind of region so it may not be illuminating an angular sector which is circular it might have in arbitrary shape so in general this half power width will depend upon the direction so if I take this direction of maximum radiation and if I take different planes passing through this quantity the half power angle would be varying.

However as we saw earlier a radiation pattern normally is taken like a two dimensional figure by taking the sections of the three dimensional radiation pattern and these two radiation pattern we call as E and the H plane radiation patterns same thing we can do for general radiation pattern also we can say that three dimensional radiation pattern what ever we had we take two sections one by plane which contains the electric field vector and the other which contains the magnetic field vector and if I take this two sections I will get the half power beam width from the two planar radiation pattern which I get by sectioning the three dimensional radiation pattern.

So I get this half power beam width in this two principle planes E plane and H plane. So I get the radiation pattern from there I get the half power beam width which could be now written as half power θ_{HP} and this could be in two planes I can call this as the E plane half power beam width or H plane half power plane width so I can say that this half power beam width is half power beam width E-plane and half power beam width H-plane. So this is a very important parameter because what this tells me is the effective angular zone in which the power will be radiated by the antenna and later on we will see essentially we make an approximation that within this region the field we assume practically constant though there is a variation one over root two and we assume that beyond this the field is suddenly dying down zero so this is the effective width over which the antenna radiates as the energy.

So this is one of the very important parameters as we mentioned this half power beam width many times it is also called 3-dB band width 3-dB b beam width because that is the angular zone over which the power variation will be fifty percent that is 3-dB.

Then we have the third characteristic of the radiation pattern and that is if I say what the effective angle is over which the radiation goes though I may accept the variation but the field should not be zero within that region so I may go as far as this nulls and then I can define the beam width between the first nulls that means if I go from the direction of the maximum radiation to the first null on this side and the first null on the other side this beam width from here to here will call as the beam width between the first nulls so this beam width we have here is theta half power and the beam width which we have from here to here is θ first nulls θ_{FN}.

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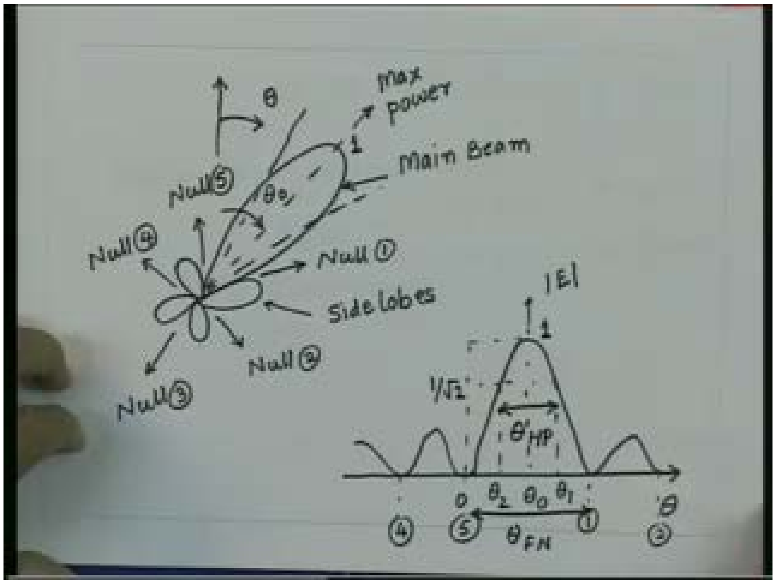

So we have the third characteristic parameter that is the beam width between first nulls we call that as BWFN.

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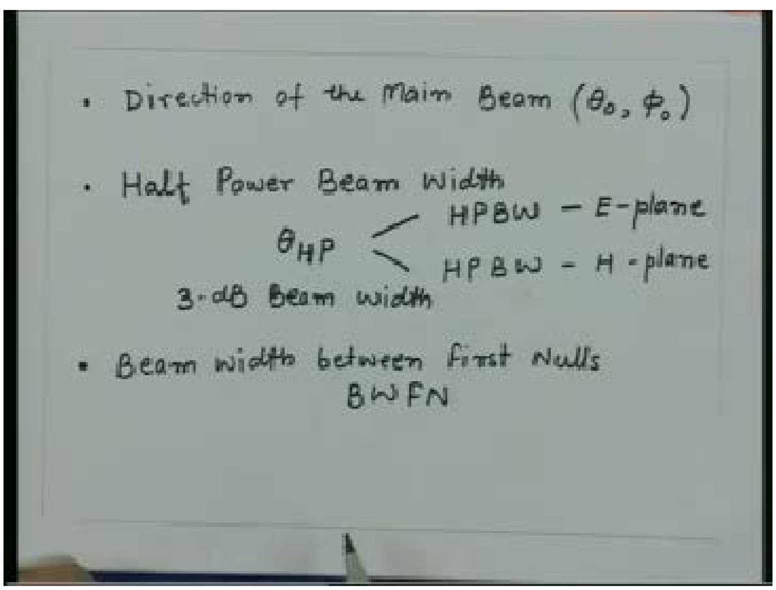

This quantity is not very reliable quantity in the sense it does not really give you the correct description of the zone over which the effective power is going. There are many antennas for which the beam width between the first nulls remains the same but the half power beam width keeps changing so basically the half power beam width that is much more reliable parameter as far as antenna description is concerned then the beam width between the first nulls. But if you take a general antenna like a antenna array or a uniform current distribution or something these two are closely related so between first nulls and the half power beam width will be closely related to each other.

The next thing which is the characteristic of the radiation pattern is that we have a main beam that means that is the direction in which the radiation goes so the antenna is designed to take the power in the direction. We also have seen that this power will go into a finite area which will be decided by the half power beam width. So that is also acceptable that this antenna is going to illuminate certain region around the direction of the maximum radiation.

However, we did not have any intension of putting power in this direction the antenna is designed to give power only in that direction. But as we saw in case of dipole or in general there will be always a direction between the two nulls where there will be small amplitude of electric field that means the power will leak out from the directions which are side lobes. So if you are designing an antenna which is very directive antenna what that means is the antenna is designed to focus power in a particular direction there will be always some leakage of power in the directions of the side lobes. So the side lobes as such are very undesirable feature of the radiation pattern and that is why in practice we try to minimize the amplitude of the side lobes. So, smaller the side lobes better the antenna because it gives you the less leakage of power in the unwanted directions.

So this measures that how much power is going to leek or what is the amplitude of the side lobe with respect to the main lobe is a parameter which is a figure of merit for a good directional antenna so the ratio of this to this. Now the side lobes need not be monotonically decreasing as we go from the maximum direction may be this side lobe will be lesser this side will be more is possible so what we do is we just find out the highest level of the side lobes that means highest value of the local maxima and ratio of main beam amplitude to that amplitude is called high lobe length.

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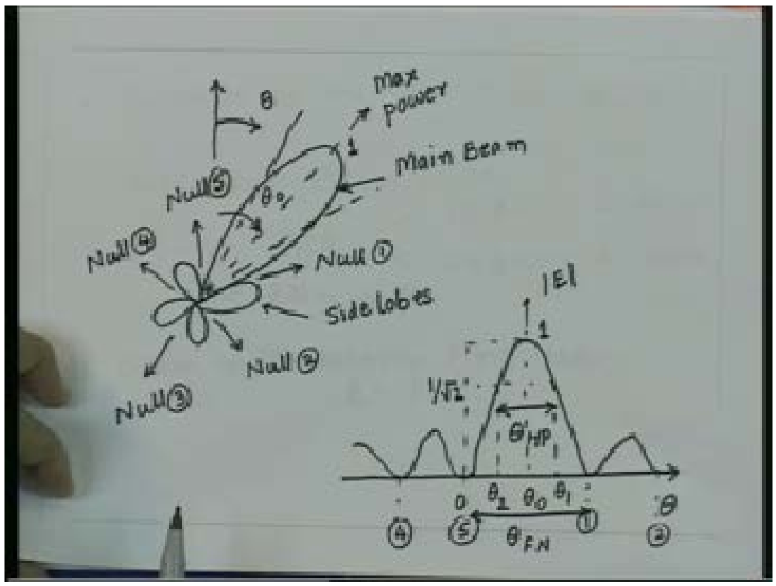

So we define this characteristic parameter called the side lobe level which is nothing but the larger side lobe amplitude divided by the main beam amplitude.

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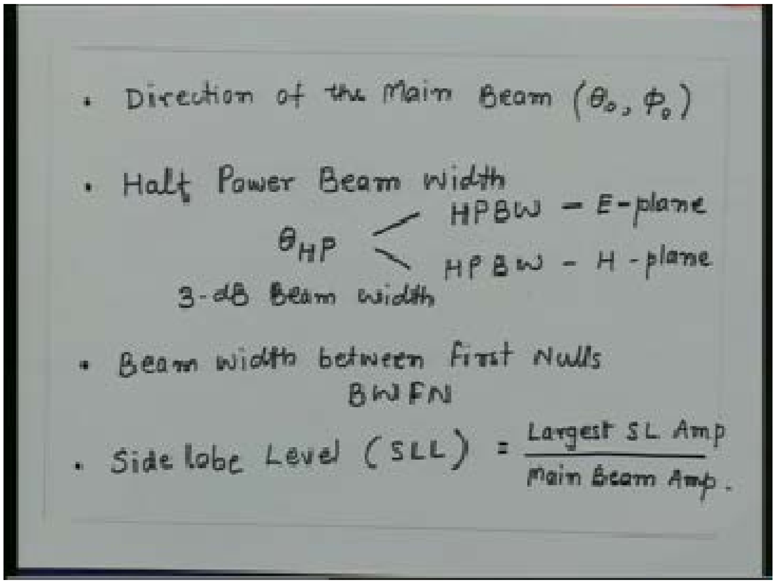

Since the main lobe amplitude is unity for normalized radiation pattern, essentially the amplitude of the largest side lobe that defines the side lobe level. Typically this number for a good antenna may lie between about twenty thirty dB so if you take the antenna which are used for example satellite communication this number would typically lie in about minus twenty minus thirty dB. We define dB as normally do this is the ratio of the two amplitude so you can take twenty log of that quantity that will define the side lobe level in dB's so that this quantity in general can be written in terms of dB's.

Now we have got these parameters from the radiation pattern like the radiation of the main beam the half power beam width of an antenna and the two principle planes the E plane and the H plane and the beam width between the first nulls and the side lobe levels for the radiation pattern. Of course we can use this quantity called the half power beam width for a relative comparison but we still require more compact parameter to represent the antennas or we require a parameter which can define really the focus and capability of the antenna that means if I want to define a very directional antenna I must have a characteristic parameter to define the focusing nature of the antenna how focusing is capability this antenna has and that parameter is called directivity of the antenna. This is a very important parameter for an antenna the directivity and the directivity essentially tells you how much capability the antenna has in focusing the power in a particular direction. So essentially we define before we do the calculation or define what directivity is.

Let us define a parameter called the radiation intensity from antenna. We have seen that if you know the electric field from the radiation pattern then we can calculate the Poynting Vector but as we go away from the antenna since the electric field dies as 1 over r the Poynting Vector which is proportional to square of the electric field that would die as 1 over r square. So the Poynting Vector which gives you the power density that means power per unit area will go on decreasing as we go from the antenna. So this parameter is distance dependent. So we define a parameter which does not depend on the distance called the radiation intensity that is the power per unit solid angle so instead of defining the power density which is power per unit area we define a parameter called the radiation intensity which is power per unit solid angle.

So we define a quantity called the radiation intensity which is power per unit solid angle. So if I calculate power in a given direction θ ø then power divided by the area gives me the power density and solid angle for a given area is the area divided by the r square from the antenna say if the antenna was here let us say I take some incremental area which is dA that is the solid angle this area subtends on the antenna so if this distance is r this solid angle dΩ is equal to dA upon r square. If I know the power in a particular direction θ ø this quantity radiation intensity U(θ, ø) will be power in the direction P(θ, ø) divided by the solid angle dΩ.

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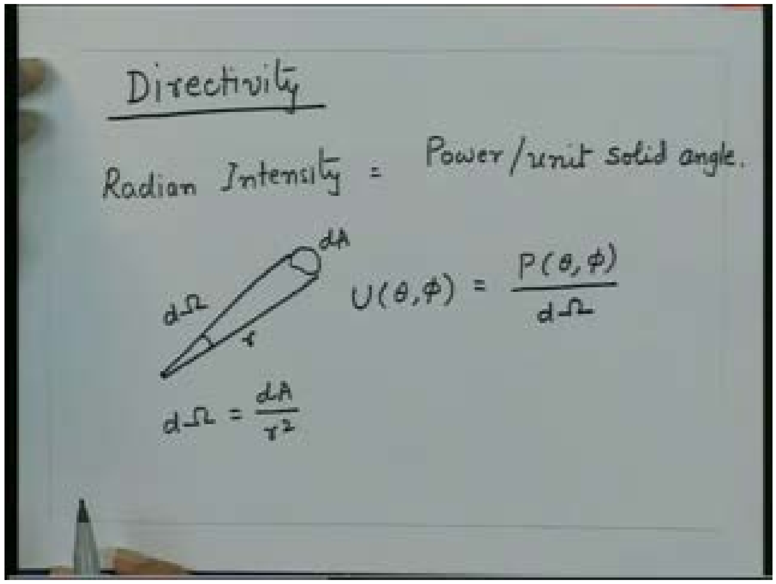

I can substitute dΩ from here so this will be a power in this cone along P(θ, ø) divided by dA into r square. But this quantity P(θ, ø) upon dA is nothing but the Poynting Vector so that gives me the power density. The radiation intensity is the power density which you get from Poynting Vector multiplied by r square. So this is essentially the power density which is the Poynting Vector so this is |E(θ, ø)| square upon η is a transverse electromagnetic wave so actually the Poynting Vector is E cross H but E and H are perpendicular to each other and H is E/η so you get the Poynting Vector which is |E| square upon η multiplied by r square and since the fields vary as one over r square essentially this r square will cancel out with that so this radiation intensity will be independent of distance and that is what is fine because ewe have to find this power per units solid angle and this angle does not change we move away from the antenna this angle is same. So the total power which remains in this solid angle is independent of the distance.

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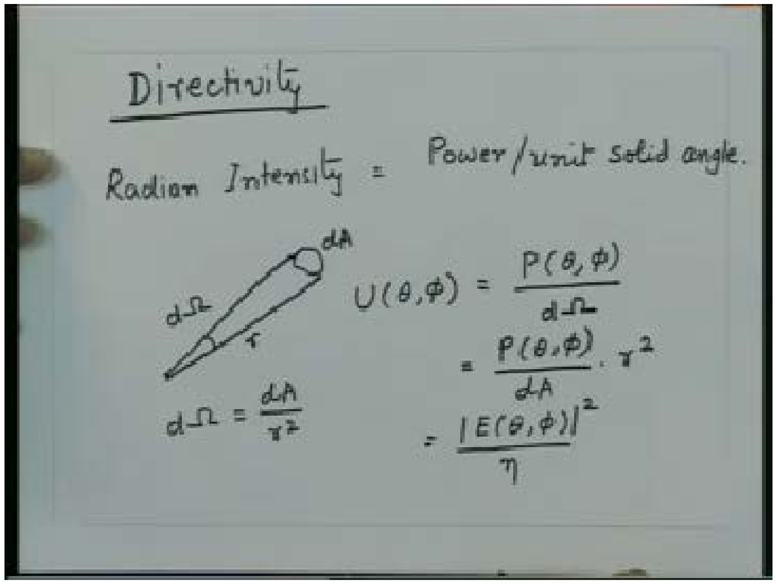

Now what we can do is once we define the radiation intensity then we can ask if the antenna was directional then how much radiation intensity it would produce in the direction of maximum radiation compared to if the radiation was uniformly distributed in all directions that means if I take certain amount of power and give it to a antenna which is very directional it will produce certain radiation intensity in the direction of maximum radiation suppose I had given the same power to a hypothetical antenna which would distribute power uniformly that means this antenna is a isotropic antenna it will produce certain radiation intensity in that direction the ratio of the two radiation intensities we call as the directivity of the antenna.

So essentially what we are saying is the directivity of the antenna is the maximum radiation intensity which you can get from the antenna divided by the average radiation intensity which you can get from the antenna because if the antenna is treated as isotropic the same power is going to get uniformly distributed for the solid angle so you will get the average radiation intensity. So now we define the power which you get here is integrated over 4π solid angle radiation intensity $U(\theta, ø)$ if I integrate over solid angle that essentially gives me the total power radiated by the antenna because this is per unit solid angle power if I integrate over solid angle then I will get total power which the antenna radiates so this one if I write specifically in terms of spherical coordinates this is θ equal to 0 to π and this is ø equal to 0 to 2π the radiation intensity U(θ, ø) sinθ with respect to the incremental solid angle dθ dø.

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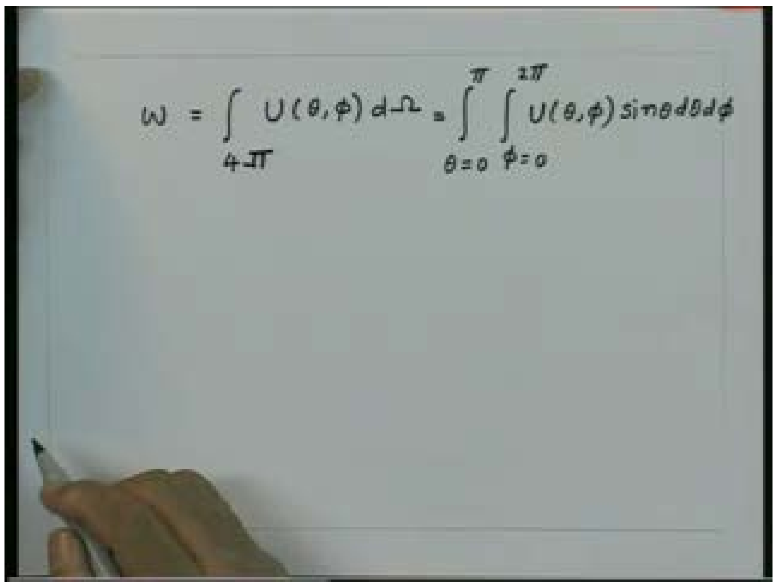

So this is the power radiated by the antenna. So if I knew the distribution of the radiation intensity then I can find out what is the total power radiated by the antenna and let us say I am taking the radiation pattern which is normalized so the maximum value of this quantity would be one so I will get normalized power essentially and if I take the actual radiation intensity then this will give me the total radiated power. So what is the average radiation intensity is this is the power now which is going to get uniformly distributed in all directions and all in directions if I take the solid angle is 4π so the average radiation intensity with this quantity divided by 4π so I get average radiation intensity U average will be w divided by total solid angle 4π so this is nothing but one upon 4π into this quantity U(θ, ø) then as we said the maximum radiation intensity which you get from the radiation patter divided by the average radiation intensity that is what we define as the directivity of the antenna so now we have the directivity as denoted by D that is equal to the U maximum divided by U average which is equal to 4π into U maximum divided by U average so this 4π will be integral U(θ, ø) dΩ.

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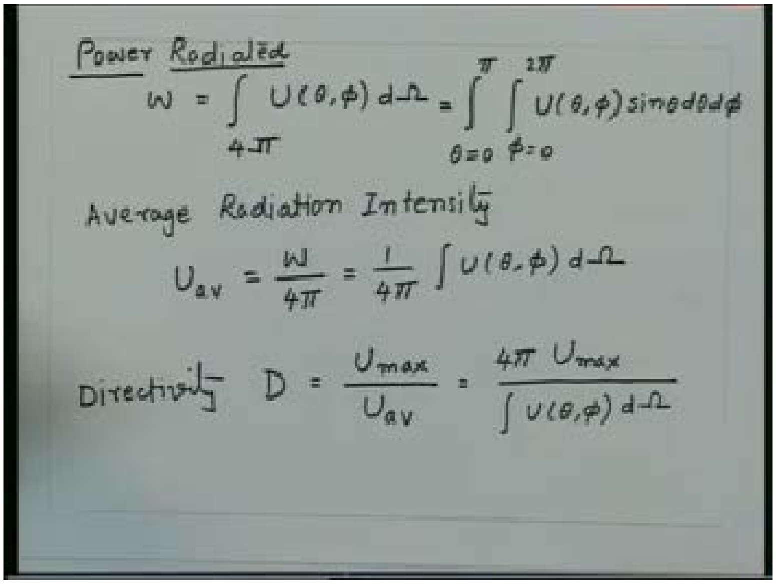

Since all the constants which are involved here since we are not interested in the absolute R calculation this variation of U(θ, ø) is proportional to the square of the electric field so in fact this quantity except the proportionality constant will be given by the square of the electric field as a function of θ and ø that is what the Poynting Vector is. S what ever are the proportionality constants they will get cancelled now this is you are taking the ratio of these two quantities so I can replace this U max by square of maximum electric field I can replace this by square of the electric field in general (θ, ø) direction and find out the integral over the total solid angle.

So I can write down the directivity in terms of the electric field D is equal to 4π |E| square maximum divided by solid angle |E|(θ, ø) square sinθ dθ dø and these are the integral θ equal to 0 to π and ø equal to 0 to 2π.

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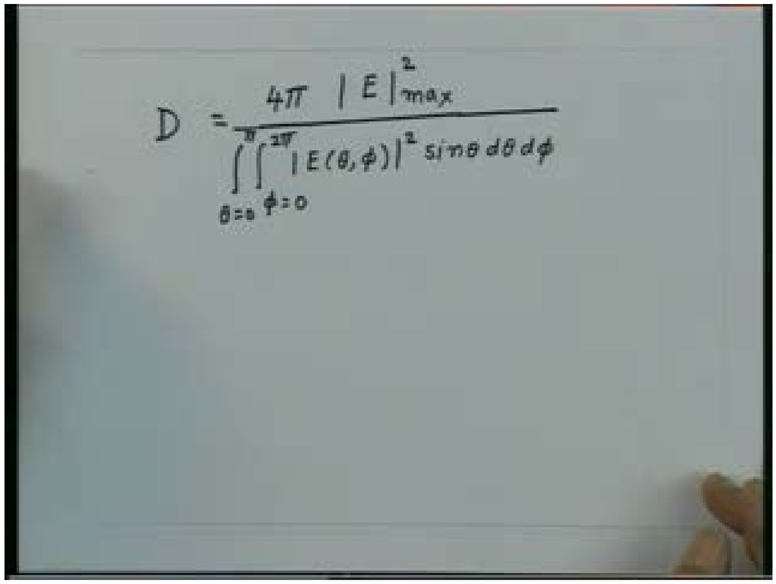

Now essentially you can get this quantity from the radiation pattern so that directivity is a parameter is purely defined by the radiation pattern and in fact since we are going again to the ratio of these quantities even the absolute value of the electric fields do not matter so even if you take a normalized radiation pattern with maximum electric field is equal to unity that means E max by definition is unity the directivity this quantity D will not get affected because what ever is again the constant it will get cancelled from here. So in general the directivity calculation you can define normalized radiation pattern which is defined by E(θ, ø) divided by $|E_{max}|$.

Then by definition this quantity is unity so we get the directivity of the antenna which is nothing but 4π divided by the normalized radiation pattern let us call this quantity as E normalized so this will be this integral E normalized (θ, ø) square sinθ dθ dø.

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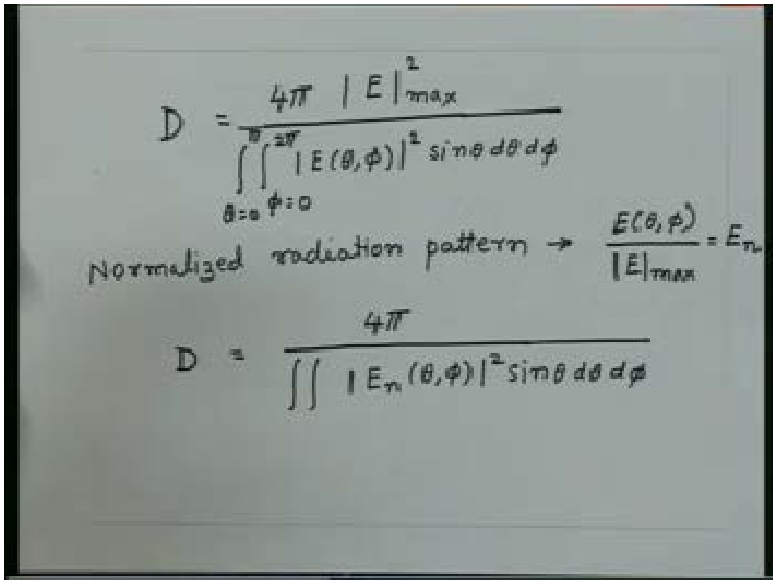

So if you know he normalized radiation pattern essentially you can calculate the directivity of a given antenna. Otherwise you can see from here essentially the directivity tells you the enhancement of the power density in a given direction with respect to an isotropic antenna. So this quantity by definition is always greater than one, for an isotropic antenna this quantity will be equal to one but any other antenna which is directional this quantity by definition has to be greater than one.

So we have D which is greater than or equal to one where the equality sign is for isotropic antenna and for directional antenna the directivity is always greater than one. And higher the value of the directivity more is the focusing power of the antenna in a given direction. Our interest is to make extremely high directional antenna then the directivity should be as high as possible, that is what is precisely done when you go to the systems like satellite antennas those antennas have a directivity which is very high they have directivity typically of order of about ten to the power five ten to the power six so they have a focusing power which is very high so the power is not wasted in any other direction the power is focused precisely in a given direction.

Now as we have done earlier if I make an approximation to the radiation pattern as we define here like this and if I say that effectively the power is confined to the half power beam width and I take two planes and let us say side lobe levels is much smaller for this antenna so I have an antenna whose radiation pattern is typically in three dimensions will be like this. So I have one plane in this plane I have half power beam width which is something the perpendicular plane and the side lobe levels are very small so practically if I see like a Cartesian coordinate system I will have radiation pattern which will look like this these are two perpendicular planes this plane and the other plane. Then I can visualize this like a box where the half power beam width for this is this the half power beam width for this is this so I can visualize this as a box of like this where this width is θ half power let us say this direction is in angle ø so this is ø half power in this direction.

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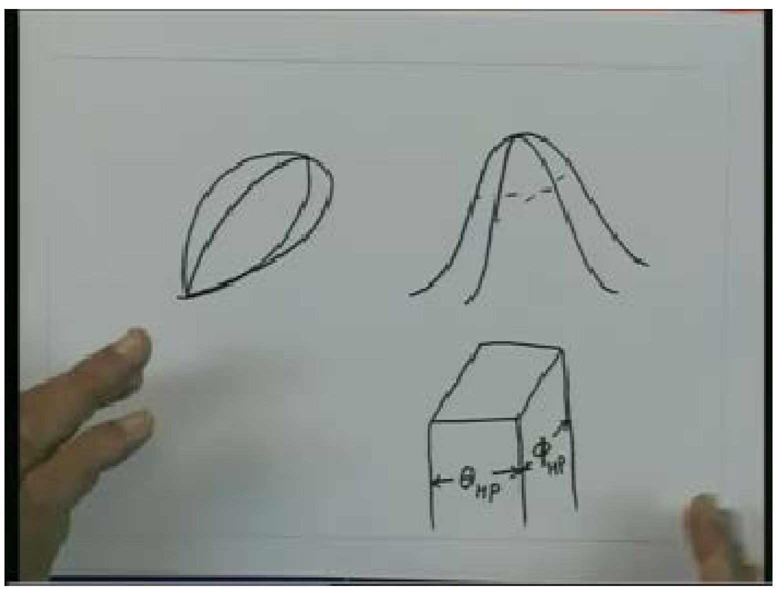

So we can make an approximation that the power is just confined to this region of half power beam width and beyond that the power is practically zero. So the integral which I require for E square essentially I can just say that this is approximated by a box which is this and so on and within this since this is a normalized radiation pattern this amplitude is one that means the height of this box is unity so the integral which we got here this thing under the assumption that this angle is very small this integral essentially is equal to the volume under this box with the height of this box equal to infinity. So essentially we get this one multiplied by θ half power, ø half power that is this quantity which will be giving you this integral.

So now we get the directivity for what is called a highly directional antenna. So if you take a very narrow beam a main beam such that your θ half power and ø half power are much smaller compared to one radian then this integral can be approximated by simply θ half power and ø half power. So I can substitute now into this so directivity approximately for a highly directional antenna is 4π divided by half power and ø half power where this θ half power and ø half power are measured in radians.

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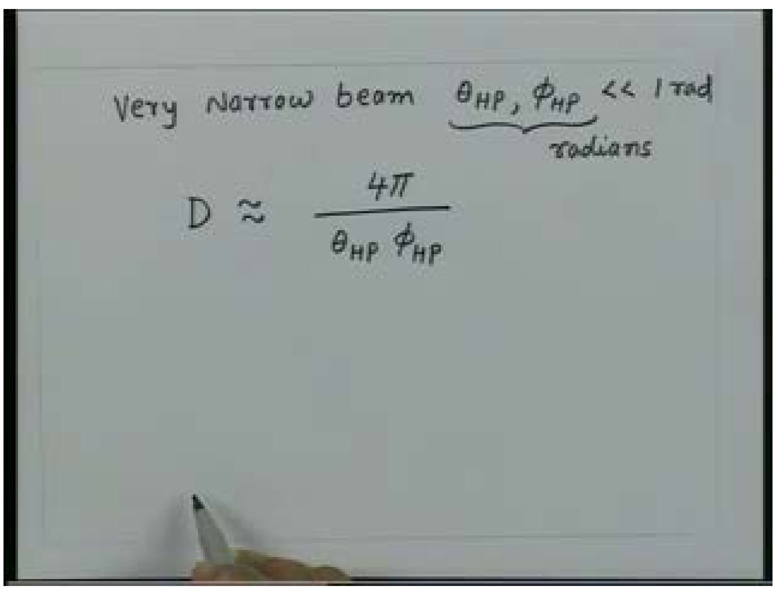

So if I could measure the half power beam width of an highly directional antenna then the calculation of approximate value of directivity is rather very straight forward. So that is why when ever we design an antenna if it is directional the first attempt is to measure half power beam width because once you measure the half power beam width then from there you can calculate this very important parameter which tells you the focusing capability of the antenna called the directivity.

By taking simple examples, suppose I have an antenna which is having half power beam width of one degree so let us say if I take a parabolic dish kind of antenna which gives me the half power beam width of one degree by one degree it produces a main beam which is circular and these both of them let us say one degrees so as an example just to get a feel of what kind of directivities are produced let us say θ half power and ø half power are equal to one degree.

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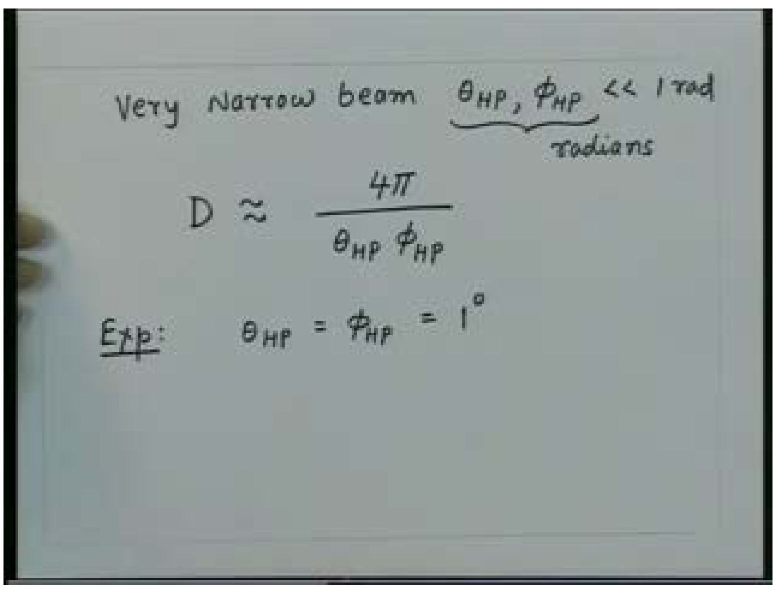

We want this in radians so this is equal to π/180 radians so the directivity for this antenna D will be 4π divided upon π/180 whole square so if I approximately calculate this value then this will be 4π, this π square will be approximately ten so this is ten multiplied by one eighty square so this will be one eighty square. So if I take this π/180 is approximately like sixty degrees that is what the approximation we can use so that gives me thirty six hundred multiplied by 4π. So you will see the directivity of this approximately will be about 4π into this quantity will be thirty six hundred so we got here the directivity which is something like thirty six to forty thousand. So if you take an antenna whose half power beam width about a degree then this antenna has a focusing power of about forty thousand.

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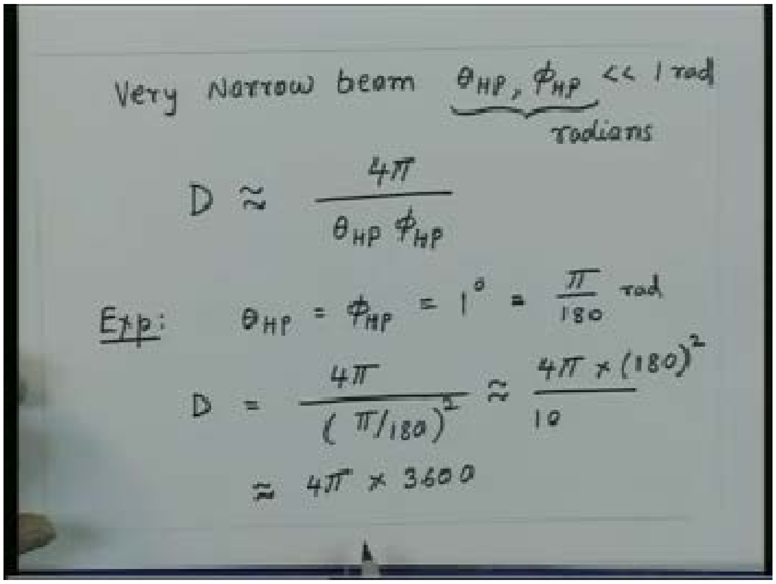

What that means is, at a given distance this antenna would enhance the radiation intensity by a factor of forty thousand and that is very interesting now and that is the reason we also call this as the gain of the antenna, that is what ever power we had if we had just thrown away the power uniformly in all directions you would have got certain amount of power there now this antenna is going to enhance the power by a factor of forty thousand say differently if I did not have this antenna and I wanted to produce this power density at a given distance I will require the power which is forty thousand times more than what I can now handle with this antenna.

So let us take a typical example suppose I wanted to have a certain radiation intensity which I would have got this antenna and let us say the power which I required was about one watt for this antenna so I take this antenna I supply one watt of power to the antenna I get certain radiation intensity at a certain distance if I did not use this antenna and if I use an antenna like a isotropic antenna then I will require forty thousand watts of power to get the same radiation intensity in that direction. Imagine a situation that let us say we want to establish a communication between the satellite and ground if this antenna was not there the power requirement will go from tens of thousands to millions so what ever communication today we are achieving today with few watts of power would mean few mega watts of power. So the antenna which looks the most passive element in the entire communication system in fact is really the heart of the communication system because if this antenna was not there the power requirement of the communication link will increase by such an order that we will not be able to realize those kind of powers.

So it is very important that when we talk about the point to point communication like microwave link or satellite communication we use the antennas which are highly directive that means the directivity is very large, by doing this essentially we are reducing the power requirement capabilities of the communication link. So the antenna essentially provides the gain in the power in certain direction of course this gain is not in the conventional sense like amplifier where the power is amplified the antenna is that means passive device so you are supplying certain amount of power to the antenna what then gain tells you is the power is enhanced in a given direction of course at the cost of other directions but in those directions we are not interested in so this gives you the enhancement of the power or amplification of the power in a given direction so this is not the increase in total power which is radiated the total power radiated is conserved is the same only thing is by antenna the power is redistributed and it is enhanced in a certain direction. So in that sense in that particular direction we can say that there is amplification of power compared to if the antenna was not there.

So, the directivity is very important parameter and this plays a very important role in reducing the power requirement in the communication link. These are the certain important characteristics of an antenna when the antenna is used as a transmitting antenna.

In the next lecture, when we meet essentially we try to look at the antenna like a receiving antenna that if the antenna is kept in the electromagnetic field how much power it will receive from the electromagnetic field. So antenna as we saw is a device which is a transducer which converts electric and magnetic fields to voltage and current and vice versa we saw one aspect converting current to field in the next lecture we will see conversion of the fields to electrical quantities like voltages and currents.

Thank you.