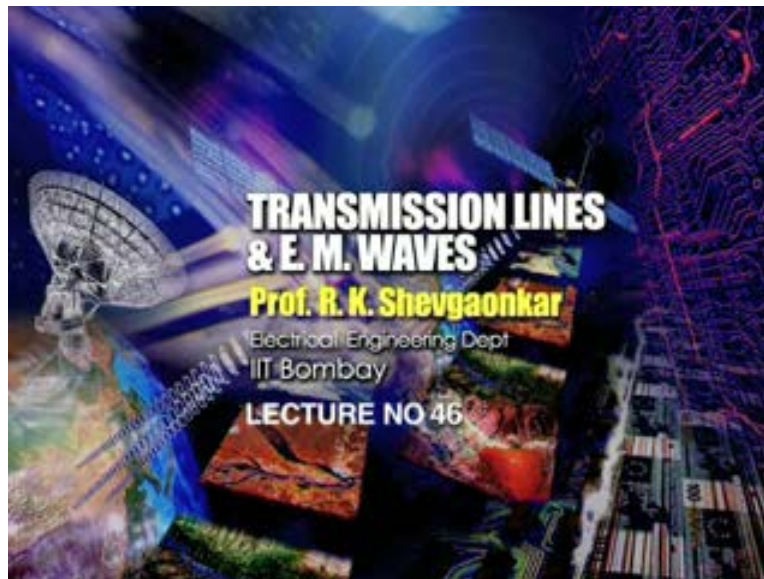


Transmission Lines and E.M. Waves
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Lecture-46

Welcome, we are investigating radiation characteristics of a Hertz Dipole. As we saw in the last lecture the Hertz Dipole is a small current element that means if you imagine a small piece of wire which is carrying some current then we can find out the vector potential due to that small current element and then from there we can find out the electric and magnetic fields.

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In the last lecture, for the Hertz Dipole which is a small current element we derived the electrode potential and the electric and magnetic fields. And we saw that for the Hertz Dipole we have a magnetic field which has only one component that is only ϕ component, whereas the electric field has two components one is the r component which is the radial component and the other one is the θ component.

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$$\begin{aligned}\nabla \times \vec{H} &= j\omega\epsilon \vec{E} \\ \vec{E} &= \frac{1}{j\omega\epsilon} \nabla \times \vec{H} \\ &= \frac{1}{j\omega\epsilon} \frac{1}{r^2 \sin\theta} \begin{vmatrix} \hat{r} & r\hat{\theta} & r\sin\theta\hat{\phi} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial \phi} \\ 0 & 0 & H_{\phi} \end{vmatrix} \\ E_r &= \frac{I_0 dl \cos\theta e^{j\omega t - j\beta r}}{4\pi\omega\epsilon} \left\{ \frac{\beta}{r^2} - \frac{j}{r^3} \right\} \\ E_{\theta} &= \frac{I_0 dl \sin\theta e^{j\omega t - j\beta r}}{4\pi\epsilon} \left\{ \frac{j\beta^2}{\omega r} + \frac{\beta}{\omega r^2} - \frac{j}{\omega r^3} \right\} \\ E_{\phi} &= 0\end{aligned}$$

we also saw that these fields have three types of variations as a function of distance from the dipole that is a field which varies as $1/r$, the field which varies as 1 over r square and the field which varies as 1 over r cube and then we understood the different phenomena which are behind these three types of fields. So we said 1 over r square field is the induction field, the 1 over r cube field is the electrostatic field which is on the ends of the current dipole you have accumulation of charges so we have essentially a bundle of charges which are sitting at the ends of the Hertz Dipole as the current oscillates these charges are also oscillate so you are having a dipole and because of that dipole you get the electrostatic field and that is given by this term so its variation is one over r cube. And then the important term in which we are interested in is the radiation field which varies as $1/r$.

So as you go away from the dipole that is the field which is the radiation field essentially dominates because these two fields die down very rapidly as we move away from the dipole.

We essentially divided the fields into these categories and then we said depending upon the distance from the dipole we can call these fields as the near field or the far field and we had a distance which is the reference distance which is $\lambda/6$ so if the distance is much more less than $\lambda/6$ then electrostatic and induction fields are dominate and we call those fields as the near fields, whereas if you go to a distance which is much larger compared to $\lambda/6$ then the dominance is by the radiation field and then we saw that radiation field has only two components which is θ for electric field and ϕ for magnetic field.

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Handwritten notes on a whiteboard:

Near Field $\rightarrow r \ll \lambda/6$
 E_r, E_θ, H_ϕ

Far Fields $\rightarrow r \gg \lambda/6$
 E_θ, H_ϕ

$$E_\theta = \frac{j I_0 dl \beta^2 \sin\theta e^{j\omega t - j\beta r}}{4\pi\omega\epsilon r}$$

$$H_\phi = \frac{j I_0 dl \beta \sin\theta e^{j\omega t - j\beta r}}{4\pi r}$$

We would also see some interesting properties for these fields that is the ratio of E_θ and H_ϕ for the radiation field is equal to the intrinsic impedance of the medium. That property is same as what we have seen for the uniform plane wave. However, in this case we have constant phase surfaces which are the spheres so we call these waves as spherical waves, however, spherical waves essentially have all the properties with the uniform plane wave have. That is the electric field and magnetic field and direction of wave propagation are perpendicular to each other and also the ratio of electric and magnetic field is equal to the intrinsic impedance of the medium.

Today, we try to see more characteristics of the Hertz Dipole and essentially we are interested in two things when we talk about the radiation one is for a given current in this Hertz Dipole how much power will be radiated in the space that means how much power will be carried by these fields second thing is, what is the directional dependence of this power flow. So the feature which captures the directional dependence is called the radiation pattern of a dipole or of an antenna in general.

So if I take the electric field and if I plot the electric field as function of angle θ and ϕ then I get a surface in three dimensions and that essentially represents the radiation pattern of the given antenna. Secondly once we have the electric and magnetic fields from the dipole then we can find out what is the Poynting Vector from this antenna we can integrate the Poynting Vector over the total surface enclosing this antenna and that will give me the total power radiated by the Hertz Dipole.

So in today's lecture we calculate the power radiated by Hertz Dipole and then we will also see radiation pattern of the Hertz Dipole. So to start with the power radiated by the Hertz Dipole we first calculate the Poynting Vector we have electric and magnetic fields so the average Poynting Vector as we have seen earlier the \bar{P}_{av} is the vector quantity that is half real part of $\mathbf{E} \times \mathbf{H}^*$.

Now since \mathbf{E} has two components θ and r and \mathbf{H} has only one component ϕ essentially we can write this as this is half real part of $E_\theta H_\phi^*$ minus $E_r H_\phi^*$ this is going to be in r direction and this is going to be in θ direction.

So the Poynting Vector has two components if I just substitute directly the electric and magnetic fields the θ and ϕ they are in right sequence θ to ϕ so the Poynting Vector will be in r direction whereas when I go from r to ϕ first of all sequences reverse that is why there is a minus sign here and the cross product of r and ϕ will be in the direction θ .

Now, one can show that if I take this electric and magnetic field expressions and I look at these fields which I have here the E_r and H_ϕ , here you have $j\beta$ upon r term for H_ϕ

whereas you have β upon r square term here. Similarly we have 1 upon r square terms here and this term is multiplied by j . So essentially there is a ninety degree phase difference between E_r and H_ϕ . So this quantity $E_r H_\phi$ when I calculate this does not have the real component because the phase difference of ninety degrees between these two components so real part contribution from this term is zero so this essentially is zero this is purely imaginary. So the real part essentially would be given by this term so that is half real part of $E_\theta H_\phi$ conjugate r cap.

We can substitute for E_θ and H_ϕ so we get the average Poynting Vector which will be half real part of I can substitute for electric and magnetic fields expressions so this is $I_0 dl \sin\theta$ divided by $4\pi r$ whole square one upon $\omega\epsilon$ and then I have terms of electric field which is $j\beta + \beta/r - j$ upon r square and because of H term which is minus $-j\beta + 1/r$.

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Power Radiated by the Hertz Dipole

$$\bar{P}_{av} = \frac{1}{2} \text{Re} \{ \vec{E} \times \vec{H}^* \}$$

$$= \frac{1}{2} \text{Re} \{ E_\theta H_\phi^* \hat{r} - E_r H_\phi^* \hat{\theta} \}$$

Imaginary

$$= \frac{1}{2} \text{Re} \{ E_\theta H_\phi^* \hat{r} \}$$

$$\bar{P}_{av} = \frac{1}{2} \text{Re} \left\{ \left(\frac{I_0 dl \sin\theta}{4\pi r} \right)^2 \frac{1}{\omega\epsilon} \left(j\beta + \frac{\beta}{r} - \frac{j}{r^2} \right) \left(-j\beta + \frac{1}{r} \right) \right\}$$

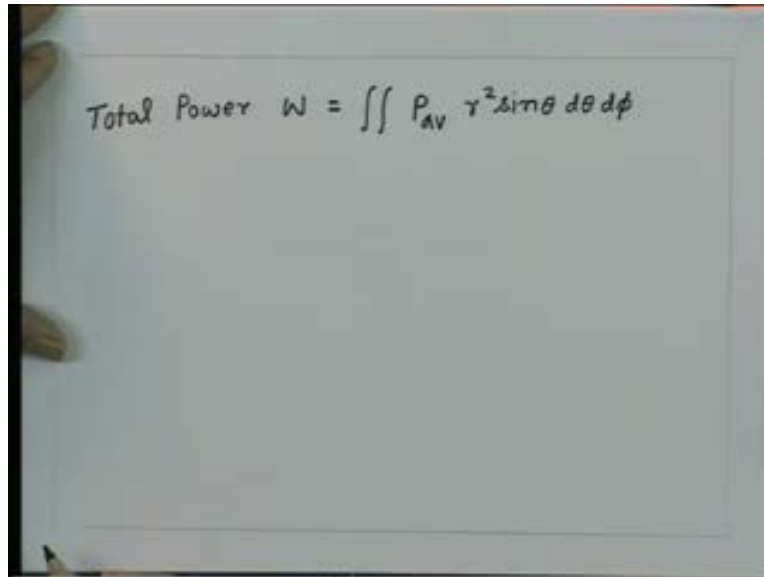
So this term is essentially coming from the electric field which is this term, whereas this term will be coming from here and we have got a minus sign here because this is H conjugate so this becomes $-j\beta$ term.

Now again if I see the terms the real terms many of the terms will cancel out so only the contribution will come only from this terms which is $j\beta$ and this quantity so essentially the real part if we calculate for this term will be equal to half $I_0 dl \sin\theta$ divided by $4\pi r$ whole square in to β square upon $\omega\epsilon$ and this quantity this will be in the direction r so it has the unit vector r so this also will be in the direction r so what that means is the Poynting Vector which you have gives you the power density that is only coming from these terms which are related to the radiation fields, other term which are having a variation is one over r or one over r square these terms do not have a real contribution to the power flow so essentially these components of the fields correspond to the reactive fields.

So when you are having this quantity purely imaginary and then you have ninety degree phase shift it is as if they are having some kind of a reactive element there so in θ direction the power oscillates one half cycle in the positive θ direction other half as negative θ direction so the power keep oscillating but there is no net power flow in the θ direction and that makes sense since there is completely a symmetric problem there is no preferred direction in which the power can flow you are having a Hertz Dipole which is oscillating so half the current will be flowing upwards, half the current will be flowing downwards so this is the preferred direction in θ in which the power can flow. So the power essentially is going to flow radially outwards which it is in direction r and it is solely going to be because of the radiation fields.

So other fields which are electrostatic field and the induction field are essentially give you the reactive fields, whereas the radiation field essentially contributes to the power flow to reflex the power from the Hertz Dipole. Once you get this thing then we can we can find out what is the total power. This is the Poynting Vector which is varying as a function of θ , now we can take any distance r take this Hertz Dipole enclosed by any closed surface integrated over the closed surface that will give me total power radiated by Hertz Dipole. For simplicity we can take this core surface as a sphere so your integration is simple so what we can do now is the total power radiated by the dipole w is equal to the surface integral p average r square $\sin\theta d\theta d\phi$.

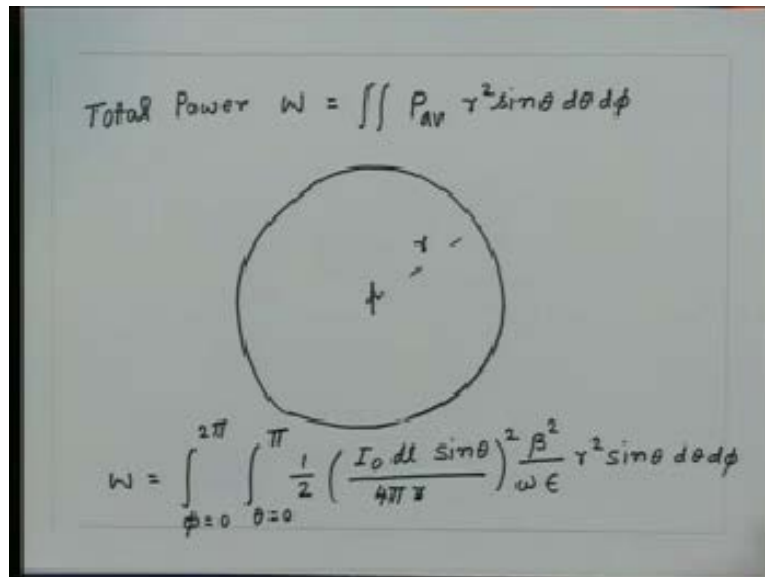
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A photograph of a whiteboard with a handwritten equation. The equation is 'Total Power W = \int \int P_{AV} r^2 \sin \theta d\theta d\phi'. The handwriting is in black ink on a white background. The equation is written in a slightly cursive style. The 'W' is capitalized. The 'P' has a subscript 'AV'. The 'r' is italicized. The 'd' is small. The 'theta' is written with a symbol. The 'phi' is written with a symbol. The equation is centered on the whiteboard.
$$\text{Total Power } W = \int \int P_{AV} r^2 \sin \theta d\theta d\phi$$

So what we have is we have Hertz Dipole here, we are considering a sphere around it of radius r so the incremental surface area on the surface of the sphere is $r^2 \sin \theta d\theta d\phi$.

So if I integrate over the total surface area that means if I integrate over all θ then ϕ and then I will get the total power radiated by the Hertz Dipole. So this integral we can write W is equal to as we know limits for ϕ is 0 to 2π , the limits for θ is 0 to π and I can write down this Poynting Vector which I have got there so this will be $\frac{1}{2} I_0 dl \sin \theta$ upon $4\pi r^2$ whole square into $r^2 \sin \theta d\theta d\phi$.

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Handwritten notes on a screen showing the derivation of total power radiated by a dipole. The text includes the formula for total power, a diagram of a sphere with radius r , and the integral expression for power.

$$\text{Total Power } W = \iiint P_{AV} r^2 \sin\theta d\theta d\phi$$

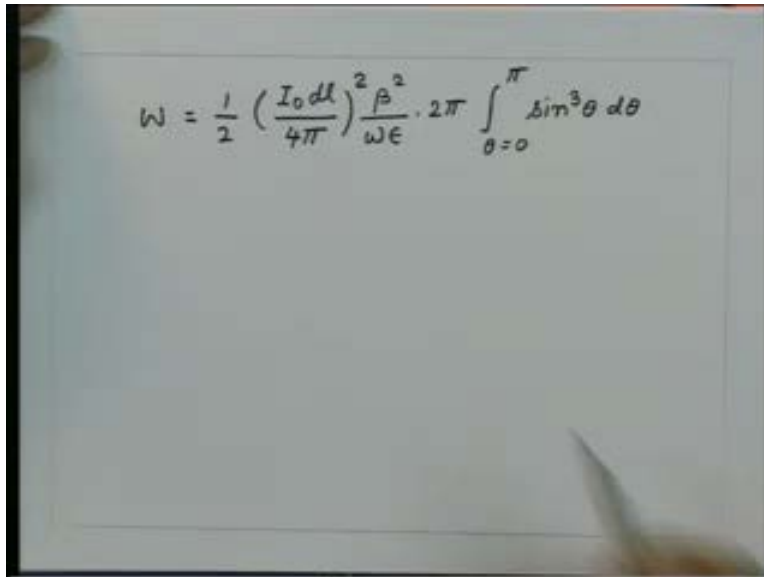
Diagram of a sphere with radius r .

$$W = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \frac{1}{2} \left(\frac{I_0 dl \sin\theta}{4\pi r} \right)^2 \frac{\beta^2}{\omega \epsilon} r^2 \sin\theta d\theta d\phi$$

The first thing to note here is this r square term is going to cancel with this r square term so the power radiated should not be a function of r because we are finding out the power which is on any surface of the sphere. So the total power which is radiated by the Dipole should not be a function of what radius we take for the sphere that should be independent of the size of the sphere that is what precisely this is telling you that this r square will cancel so total power will be independent of what radius for the spheres you take.

So if I just substitute now, there is no ϕ variation in this expression so ϕ integral is very straight forward it will give me the value 2π and integral is essentially over this θ . So I will have θ square and this $\sin\theta$ will give me sine cube θ . The power radiated w will be equal to half $I_0 dl$ upon 4π whole square into β square upon $\omega\epsilon$ where integral over ϕ will give me 2π integral θ equal to 0 to π sine cube $\theta d\theta$.

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A photograph of a whiteboard with a handwritten equation. The equation is:
$$W = \frac{1}{2} \left(\frac{I_0 dl}{4\pi} \right)^2 \frac{\beta^2}{\omega \epsilon} \cdot 2\pi \int_{\theta=0}^{\pi} \sin^3 \theta d\theta$$

The handwriting is in black ink on a white background. The equation is centered on the board. A pen is visible in the bottom right corner of the frame.

Now this integral is very straight forward I can write down the sin cube θ as sine square θ $\sin\theta$ and I can write down the sin square θ as $(1 - \cos^2 \theta)$. So this integral as I said this is some I_1 where I_1 will be some integral θ equal to 0 to π if we write sin square θ $\sin \theta d\theta$ and this we can write as $(1 - \cos^2 \theta) \sin\theta d\theta$ putting $\cos\theta = t$, $-\sin\theta d\theta$ will be equal to dt .

So this will be the integral $(1 - t^2) dt$ and the limits when θ is equal to zero this t will be equal to one and θ will be equal to π then this will be equal to -1 so I can substitute into this and I have a negative sign for $\sin \theta$ I can change the limit from -1 to 1 so the integral value will be essentially $4/3$.

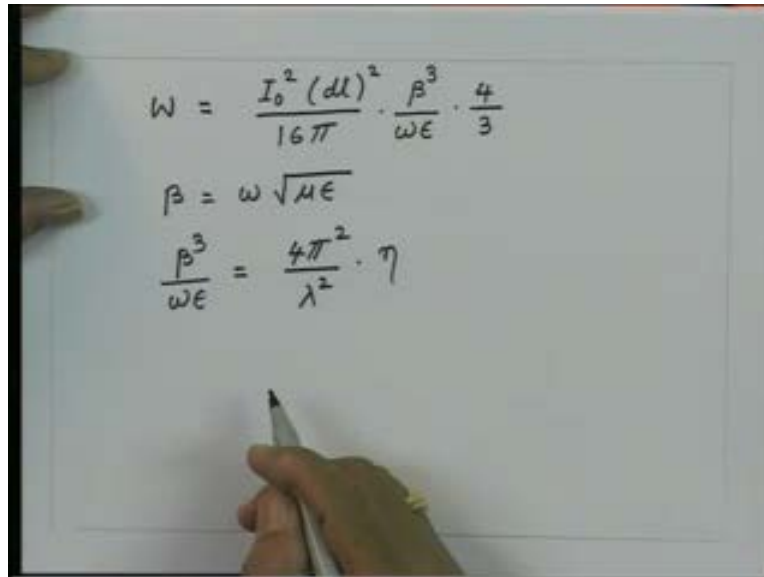
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$$\begin{aligned}
 W &= \frac{1}{2} \left(\frac{I_0 dl}{4\pi} \right)^2 \frac{\beta^2}{\omega \epsilon} \cdot 2\pi \underbrace{\int_{\theta=0}^{\pi} \sin^3 \theta d\theta}_{I_1} \\
 I_1 &= \int_{\theta=0}^{\pi} \sin^2 \theta \sin \theta d\theta \\
 &= \int_{-1}^1 (1 - \cos^2 \theta) \sin \theta d\theta \\
 &= \int_{-1}^1 (1 - t^2) dt \quad \text{putting } \cos \theta = t \\
 &\quad \quad \quad -\sin \theta d\theta = dt \\
 &= 4/3
 \end{aligned}$$

Now I can substitute for the integral value into this expression and then I get the total power radiated by the Hertz Dipole w that will be equal to this which will give me sixteen π square into two so it is thirty two which cancels with these two so I will get a sixteen so that gives me I_0 square dl square upon 16π into β cube upon $\omega \epsilon$ into $4/3$.

Now if I write down here for β that is β is equal to ω square root of $\mu \epsilon$, essentially this quantity here ω cube upon $\mu \epsilon$ will become essentially 4π square upon λ square into η where η is the intrinsic impedance of the medium.

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A photograph of a whiteboard with handwritten mathematical equations. The equations are:

$$W = \frac{I_0^2 (dl)^2}{16\pi} \cdot \frac{\beta^3}{\omega\epsilon} \cdot \frac{4}{3}$$
$$\beta = \omega \sqrt{\mu\epsilon}$$
$$\frac{\beta^3}{\omega\epsilon} = \frac{4\pi^2}{\lambda^2} \cdot \eta$$

A hand holding a pen is visible at the bottom of the frame, pointing towards the equations.

If I rearrange some terms into this and substitute, for that I will get the total power radiated by the Hertz Dipole that can be written in terms of the intrinsic impedance substituted here and if I take the radiation is taking place in the free space this quantity is 120π . So this one you know for the free space is 120π so I can substitute here for 120π .

So by substituting this into this expression essentially we get the total power radiated will be 40π square I_0 square dl upon λ whole square. So for a given current I_0 remember the I_0 is the peak current because we have taken the variation of the current I_0 will be $j\omega t$. So this I_0 is the peak current which is flowing in the current element the total power radiated will be proportional to the square of the current that is normally the case when ever we talk about the power, the power is proportional to the square of the current so that is true in this case also.

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$$\begin{aligned}
 W &= \frac{I_0^2 (dl)^2}{16\pi} \cdot \frac{\beta^3}{\omega\epsilon} \cdot \frac{4}{3} \\
 \beta &= \omega \sqrt{\mu\epsilon} \\
 \frac{\beta^3}{\omega\epsilon} &= \frac{4\pi^2}{\lambda^2} \cdot \eta \leftarrow \begin{array}{l} \text{for Free space} \\ \text{is } 120\pi \end{array} \\
 W &= 40\pi^2 I_0^2 \left(\frac{dl}{\lambda} \right)^2
 \end{aligned}$$

However, what we note is the power radiated is related to the square of the length of the Dipole normalized to the value that is λ that means the absolute length of the Dipole is not important but what is important is the relative length of the Dipole with respect to the wavelength which is radiant. So as the λ becomes larger and larger that means the frequency comes down this dl can be taken physically large enough so that even then we can satisfy the condition for the Hertz Dipole that is the current is constant along the length and we can apply this formula to calculate the power radiated by the Hertz Dipole.

So the power radiated is proportional to the physical length of the Hertz Dipole for a given frequency or for a given λ . Does that mean that by increasing the value of dl arbitrarily we can increase the power radiated, the answer is no, we can increase the value of dl but we still have to maintain the nature of Hertz Dipole and the current along the Hertz Dipole is uniform. We have seen right from the beginning of this course we can assume the current to be uniform when the size of the structure is much smaller compared to the wavelength. So for the uniformity of the current along the Hertz Dipole the length must be much much small compared to λ so we can say that I can change the value of dl I

can increase it but still I have to keep this quantity dl much smaller compared to λ so that I can call this structure still a Hertz Dipole.

So I do not have really too large variation in dl because the dl can be ten percent or less than that to satisfy the condition that the current is uniform across the length of the Dipole. But within that range if I increase the length of the Dipole then the power is going to increase for a given current and that relation will be this square relationship with the length of the Dipole.

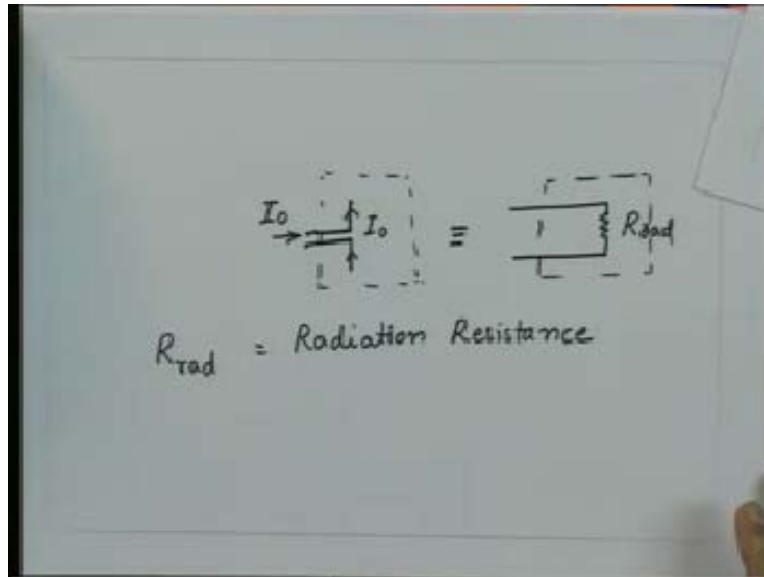
So now this thing tells me that as long as the structure is much smaller compared to the wavelength I can treat this structure as a Hertz Dipole and then just by using the concept which we have developed we can calculate the power radiated by the Dipole.

Now if I look at this antenna from the circuit point of view the Hertz Dipole we can excite this antenna by some voltage source which will give me the current in the terminals. So let us say if I break the Hertz Dipole half way this is my Hertz Dipole which has broken in two parts and this is the input through which the current is flowing so if this is connected to a circuit the current I_0 comes like this it flows through that from here it comes back so you are having a current which is flowing I_0 in the terminals of the antenna so this current is I_0 . So if I see from the input terminal side since the antenna is radiating and this power is now going away from this structure if I enclose this antenna in a black box if I treat it like a black box and just observe the characteristic only on the terminal of this antenna it will appear we have a current I_0 going inside the terminals of the antenna and so much power is radiated by the antenna that means this box has consumed so much of power.

So if I treat this hertz Dipole like a black box this black box will appear like resistance when the current comes into that there is a power loss inside it and that is the characteristic of resistance. So I can say equivalently this is to this box here which is the black box and which is equivalent to some resistance same power as radiated by the Hertz Dipole. Since this resistance is related to the power radiated by the Hertz Dipole we

call this resistance as the radiation resistance of the Dipole and let us denote that by R_{rad} so this quantity R is Radiation Resistance of the Hertz Dipole.

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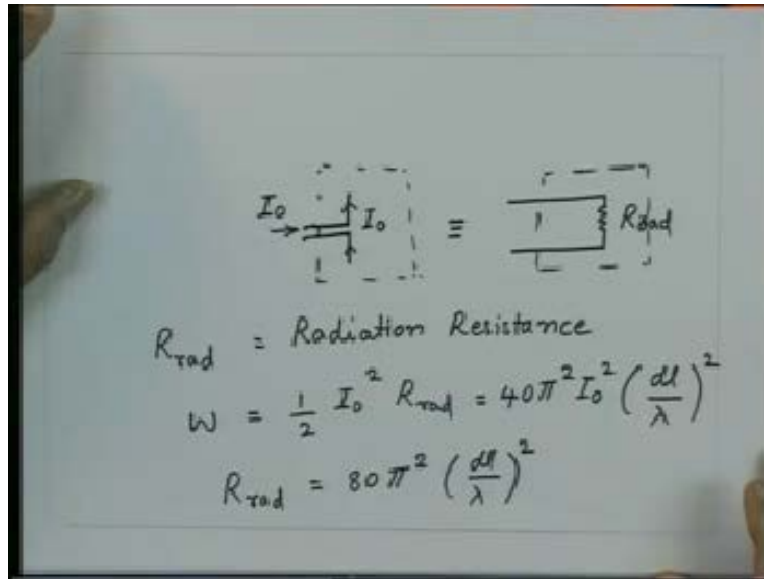
So if I see this Dipole from the circuit point of view then this is equivalent to this radiation resistance. Of course, it will appear like resistance if we concentrate only on the radiation fields which are contributing to the power flow but as we know in the vicinity of the Dipole we also have the electrostatic and the induction fields which are reactive fields. So in fact between the terminals of this antenna you will not get only radiation resistance but you will also get the reactance which will be corresponding to those electrostatics and induction field.

So in general the antenna will appear like a complex load the real part of this load will correspond to the power radiated by the Dipole. So if that is then I can ask the power consumed by this one if I go by simple circuit point of view will be simply half I_0^2 into R_{rad} the Radiation Resistance. So, from the circuit point of view the w should be equal to half I_0^2 square into the radiation resistance, equating these two, this is the power which is radiated by the antenna this is the power which is now wound into the terminals

of the antenna these two should be equal this is equal to 40π square I_0 square dl upon λ square.

So I_0 will cancel out and from here we get the radiation resistance of Hertz Dipole that is equal to 80π square into dl upon λ whole square. And as we have seen the power radiated is proportional to R radiation for given current, higher the radiation resistance more will be the power radiated by the Hertz Dipole.

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$$R_{\text{rad}} = \text{Radiation Resistance}$$

$$W = \frac{1}{2} I_0^2 R_{\text{rad}} = 40 \pi^2 I_0^2 \left(\frac{dl}{\lambda} \right)^2$$

$$R_{\text{rad}} = 80 \pi^2 \left(\frac{dl}{\lambda} \right)^2$$

Now we are having a requirement that radiation resistance should be as large as possible that essentially means dl should be as large as possible but dl cannot be increased arbitrarily large so we have a limited range of dl that means we have a limited value of the radiation resistance. If I say the rule of thumb when the length is about ten percent of the wavelength we can call that is much smaller when compared to λ if I take $dl = 0.1\lambda$ this ratio will be 0.1 square of that will be 0.01 .

So the radiation resistance will be approximately eight ohms, this π square will be approximately ten. So if I take dl approximately 0.1λ then the radiation resistance for this will be approximately eight ohms which is a very small resistance.

Firstly, if I want to excite this structure I will be using some transmission line for connecting this and we have seen that coaxial kind of structure we are having characteristic impedance which are of the order of fifty ohms if I take a parallel wire line for connecting this then the characteristic impedance will be few hundred ohms so practically this load appears almost goes to short circuit compared to the characteristic impedance. You have a great mismatching problem between the transmission line and the antenna when you try to excite this antenna.

Secondly, because of the low radiation resistance the power radiated by this antenna is very small. So radiation resistance is a good concept when we try to estimate the power radiated by a given antenna and then by devising the mechanism by which the radiation resistance can be increased we can radiate more power for a given excitation current in the antenna.

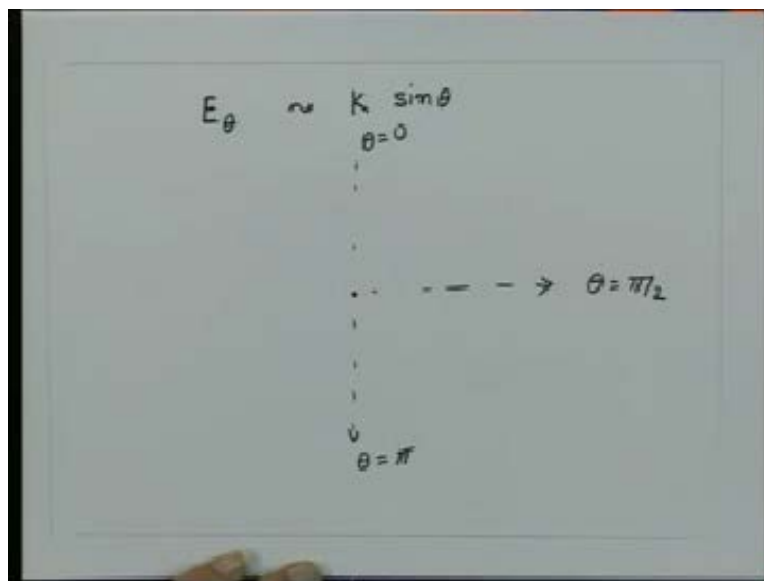
Having done this calculation now for the power radiated by the antenna we can go to the directional characteristics of the antenna and as I mention this is captured by the radiation pattern of the antenna.

So here we are not interested in the absolute electric and magnetic fields what we are interested is how this electric and magnetic field is varying at the function of the angle from the Dipole. If I consider the radiation field that is what we are interested in then what is the variation of E_θ and H_ϕ at the function of the angle θ and ϕ . So if I plot a spherical plot in which the radius vector is amplitude of the electric field and if I plot the electric field as the function of θ and ϕ I will get a three dimensional surface and I call that as the radiation pattern of the antenna.

Now all these which I am having $I_0 dl \beta$ square are taken as constant because we are interested only in the relative variation of the electric field as a function of θ and same is true for ϕ for radiation field because ratio of E and H is equal to intrinsic impedance that means constant that means the radiation pattern which we get for electric and magnetic fields is exactly identical. Since now we are interested only in the relative fields these factors do not matter so essentially we have a variation for the electric field which is E_θ that varies as some constant which includes all those factors like current and length of the Dipole the wavelength and so on and the variation which is sine of θ .

So note the variation of this field in θ plane is $\sin\theta$ so now if I consider this is the location where the Hertz Dipole is located and the amplitude is not the distance the distance is telling me this amplitude of the electric field. So if I plot the electric field as the function of θ for only the radiation fields then I will get this plot what we call as the radiation pattern. So if I put $\theta = 0$ which is this direction so this direction is $\theta = 0$ this direction is equal to $\theta = \pi/2$, this direction is $\theta = \pi$ and the range of theta is from 0 to π and then you have ϕ variation which goes from 0 to 2π which is in this direction. So the electric field does not have a variation in ϕ that means we have symmetry in the ϕ plane.

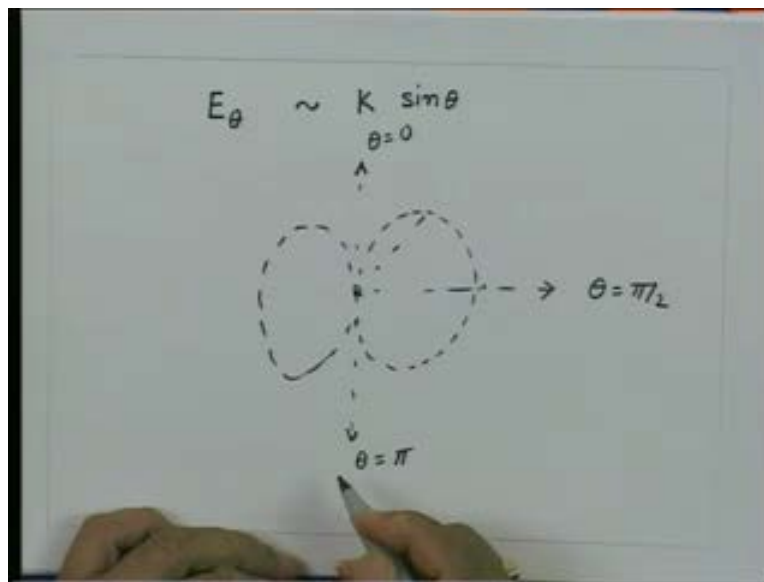
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So when $\theta = 0$ the field is zero, when you go to θ equal to forty five degrees you will have K upon root two and since we are only interested in relative distribution we can as well take case one so we have some distance which is 1 over root 2 at forty five degrees when I take $\theta = \pi/2$ this will be equal to 1, again when I go to one thirty five degrees it will be one over root two and when θ becomes equal to π again the field will go to zero so the field variation will be something like that if I vary the value of θ fix some value of ϕ and plot this and that is the variation essentially I am going to get as the function of θ .

And now since it is circularly symmetric I take this pattern and revolve it around this axis which is the axis of the Hertz Dipole so around this line which is z axis if I take this pattern and revolve it I will get a three dimensional figure and that is what we call as the radiation pattern of the antenna.

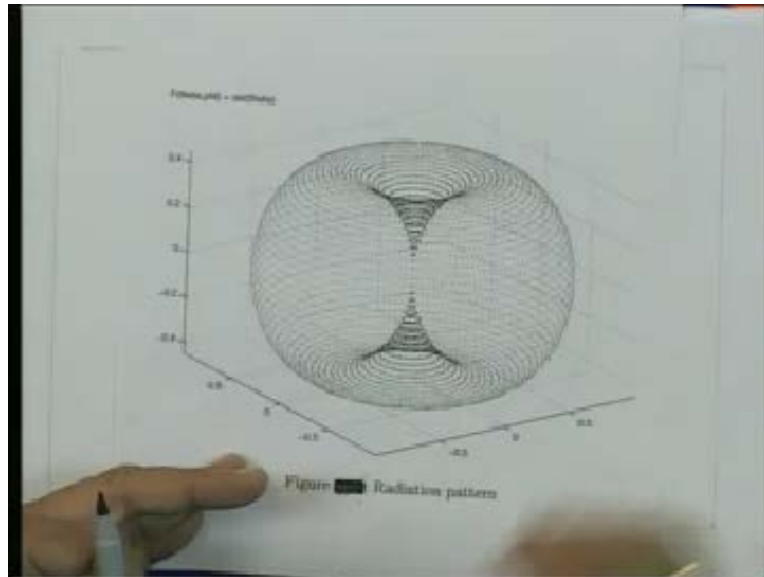
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So if I visualize this in three dimensions then the structure essentially would look something like that. Here the antenna its size and all that are not given or not shown what is shown is the antenna is taken as a point and the field which is coming from that point

are having a variation $\sin\theta$ so I plot the amplitude of the electric field as a function of θ and ϕ I will create a surface which will look something like apple.

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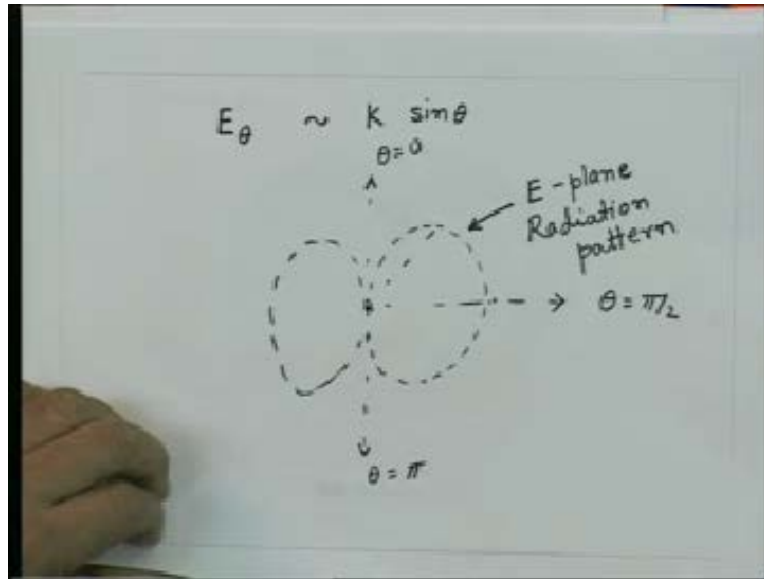
So the radiation pattern of the Hertz Dipole is like an apple, remember also the radiation pattern is the three dimensional figure. So essentially we are drawing the variation of electric field as a function of θ and ϕ therefore we will get this three dimensional surface and that is what we call as the radiation pattern.

However, while drawing or discussing it is rather difficult to draw three dimensional figures and since this is a simple figure so if you take sections of this figure we can still get the information about the three dimensional figure. So what we do is we take two sections of this figure by two principle planes, one is the plane which is in the ϕ plane and the other one is the plane which is the θ plane.

So the θ plane is the one which the plane which passes through the axis and the angle if I take some point here the plane which contains that point and that plane essentially will be θ plane. In this case this plane of the paper is nothing but θ plane so if I take this apple

and cut it vertically I will get pattern which will look like that so this is the variation of the electric field in the θ plane that is the reason I call this radiation plane pattern as the E plane radiation pattern because the electric field is going to lie in this θ plane the electric field does not lie in one component which is θ component so this is the plane which is the plane of the paper in which the vector field E is line so the electric field as we saw essentially in the direction θ so electric field vector lies in this plane so we call this radiation pattern as E plane radiation pattern.

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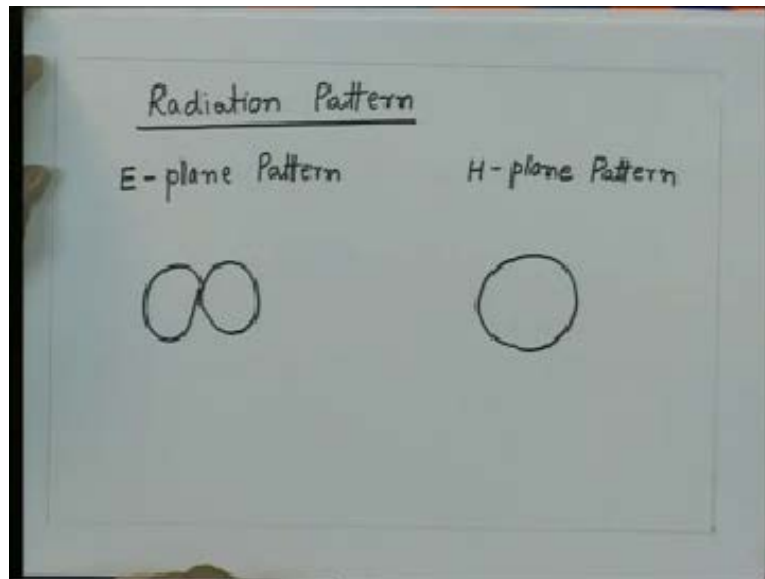
The other principle plane by which we can cut this three dimensional figure is plane perpendicular to θ which is the horizontal plane and that plane if I cut this figure at this location where $\theta = \pi/2$ I will get a figure which will be a circle and since the magnetic field is having a component which is only ϕ component this plane essentially contains the magnetic field vector.

So we call this horizontal plane as the H plane and the variation of electric field is this plane as H plane we call as the H plane radiation pattern. Now we got the sections of this general three dimensional surface by two principle planes, one is the E plane and the

other is H plane. So this three dimensional figure can be described by two planar figures which are sections of this three dimensional surface in two planes and we will call these patterns as the E and H plane radiation patterns.

Here we get two radiation patterns so we have a pattern called the E plane pattern and we have got H plane pattern. The E plane pattern is like figure of it whereas the H plane pattern is the circle. So generally when we discuss about the antennas since this figure is very simple most of the time the radiation patterns are given in H plane which is complicated for the Hertz Dipole or Linear Dipole and because of the circular symmetry the H plane radiation pattern is always a circle. So in the books essentially we see the patterns which will be this and it is basically assumed that H plane radiation pattern we know and that is the circular pattern. But we must always remember that although normally these two sections for this three dimensional figure are given as radiation patterns the radiation pattern is actually a three dimensional circuit which should always be remembered because many times if you do not remember that we might come to wrong conclusions that if we do not visualize the radiation pattern properly in the three dimensional figure then it is possible that you might conclude something wrongly. So we should always develop a habit of visualizing the radiation patterns in three dimensions we should always remember radiation pattern is a function of θ and ϕ though we might have simpler sections of that pattern and we can call that pattern as E plane or H plane radiation pattern.

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So the radiation pattern is a very important aspect of antenna what it tells is me which direction the power is going and as we saw the power is proportional to $\text{mod } E^2$ so the power is maximally going in this direction no power goes in this direction. If I look for this radiation pattern in the three dimension the maximum power is going in the plane which is perpendicular to the Hertz Dipole so Hertz Dipole is oriented this way that is where the Dipole was oriented along the Dipole there is no power flow and that is a very important thing that if I consider an antenna which is like a Hertz Dipole there will not be any power radiated along this axis the whole power will be radiated perpendicular to that and in this case the power will be radiated symmetrically in all directions so the antenna has the preferred direction for throwing the power it does not through the power uniformly in all directions.

Now the Hertz Dipole is the simplest possible antenna we have thought of because when ever we have current there is a direction there so what we said even if we take the simplest possible case of a current which does not have any special size but which has just the orientation that is what the Hertz Dipole did it had a preferred direction for throwing away the power that means I can never have a system which will throw power

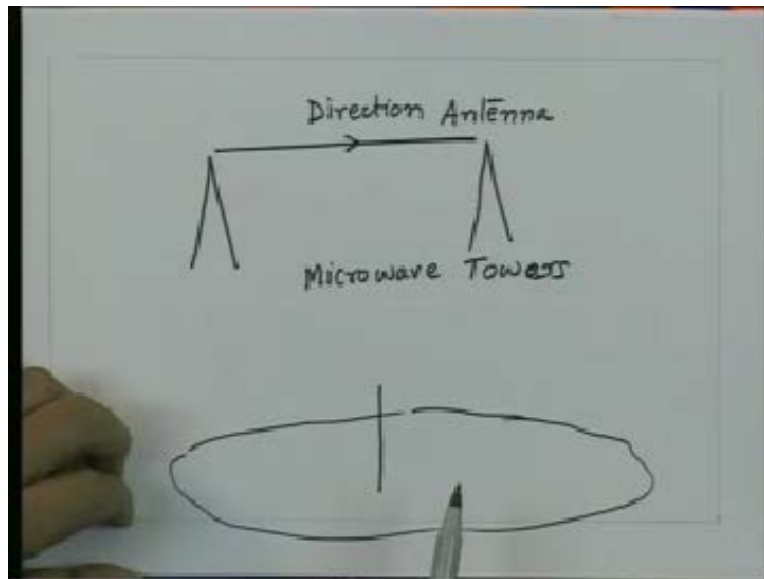
uniformly in all directions because even the simplest current element has put the power preferably in some directions. So this nature that now the power is not going uniformly in all directions is the directional nature of the antenna and that is very important so it is very difficult or impossible rather to realize in fact is an isotropic antenna which will throw away the power equally in all directions.

Now depending on the applications we may require the directional dependence very strongly there are many situations where we may not require this directional dependence at all.

Let me give you an example that let us say I want to establish communication between two points as we do for example in microwave towers which we see around us so I have a microwave tower here, I have a microwave tower here and the interest is essentially to send the power from this location to this location with as minimal loss as possible.

In this case I would prefer to have an antenna which will be highly directional that means this antenna should put power only in this direction and should not give the power in any other direction so my radiation pattern should be such that it is maximum in this direction and very rapidly dies down as I move away from this direction. So I will require a highly directional antenna in this case. However, imagine a situation this is a radio station this is the microwave tower the other situation is I have a radio station and there is a city around it and we want to have broadcasting from this radio station. Obviously, now we are not interested in sending the radio signal from the radio station to a particular house we want to distribute the power as uniformly across the city as possible so we have a region which is around this where the radiation should go as uniformly as possible.

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In this case I require an antenna which is as isotropic as possible that means it should not have directional dependence. As we argued it is not possible to get an isotropic antenna in practice so you might get an isotropic nature may be in a plane and that is what your Hertz Dipole does. This radiation pattern is not uniform in all directions but if I go in a direction in the H plane my radiation pattern is the circle that means if I ask what is the nature of the radiation pattern in this plane which is H plane that is isotropic it is not isotropic as a function of θ but it is isotropic as a function of ϕ .

So I may use this structure and I may get a radiation pattern which is uniform in this direction for making use for the broadcasting applications. So in this case I may have an application which will broadcast. Depending upon the situation I may require an antenna which is very directional that means it has a strongly preferred direction for putting the power or I may require an antenna which does not have any preferred direction so that the power goes uniformly in its surrounding. So in broadcasting application I will get an antenna which is isotropic which is non-directional whereas for microwave tower kind of application I will get an antenna which is highly directional antenna.

Having understood this then now depending application we might require to design the antennas which will have a special radiation characteristics like radiation patterns, also in a physical system for a give current we would like to radiate more power so ideally the Hertz Dipole though it is very nice it should develop the concept of radiation the Hertz Dipole as such will not be a useful device what we have more useful is you take the length of the wire which is essentially the Hertz Dipole but now if I increase the length which becomes compatible with the wavelength I can assume the current to be uniform across the Dipole but I can still visualize this linear wire as collection of small small Hertz Dipoles and now there is a possibility that this structure which is more realizable structure will give more radiation. Of course, in this process your radiation pattern also will get modified.

So, that next time when we meet essentially we talk about a more practical antenna which is very commonly used is what is called a Linear Dipole Antenna. So Linear Dipole Antenna is simply a linear structure like a wire which is excited with some voltage the current flows on this wire and then visualizing this wire as collection on the Hertz Dipole we calculate the electric and magnetic fields and then we calculate the power and radiation patterns and other aspects of the Linear Dipole.

So in the next lecture we will investigate the characteristics of more physically realizable antenna called the Dipole antenna.

Thank you.