Radio Astronomy

Prof. Abhirup Datta

Department of Astronomy, Astrophysics, and Space Engineering

Indian Institute of Technology Indore

Lec-09

Fundamentals of Antenna

Hello, welcome to this third week lectures on radio astronomy. This week we'll concentrate on fundamentals of antenna theory. In the past two weeks I think we have been able to persuade you to understand the importance of radio telescope. The faint signals which we receive from the cosmic sources really need a great deal of attention and mastery in electronic circuits to be able to amplify the signal and reduce the noise before it gets detected and we do useful science out of it. So antenna is one of the very important block in this entire system of radio telescope and we will be concentrating on that quite deeply in this particular week. To begin with the background which we have discussed briefly about Maxwell's equation, some part of the pointing vector, the radiation will be very useful to understand how basic antenna radiates and we will start from there and we will go slowly step by step.

So let's start. So this particular week we have, we will discuss the antenna, what is a radio antenna, why we need an antenna, importance of antenna by application, antenna fundamentals, how does antenna radiates. We start with a particular example of Hertz Dipole. Then how do we characterize an antenna, the radiation pattern, gain, directivity, radiation impedance, effective area, etc.

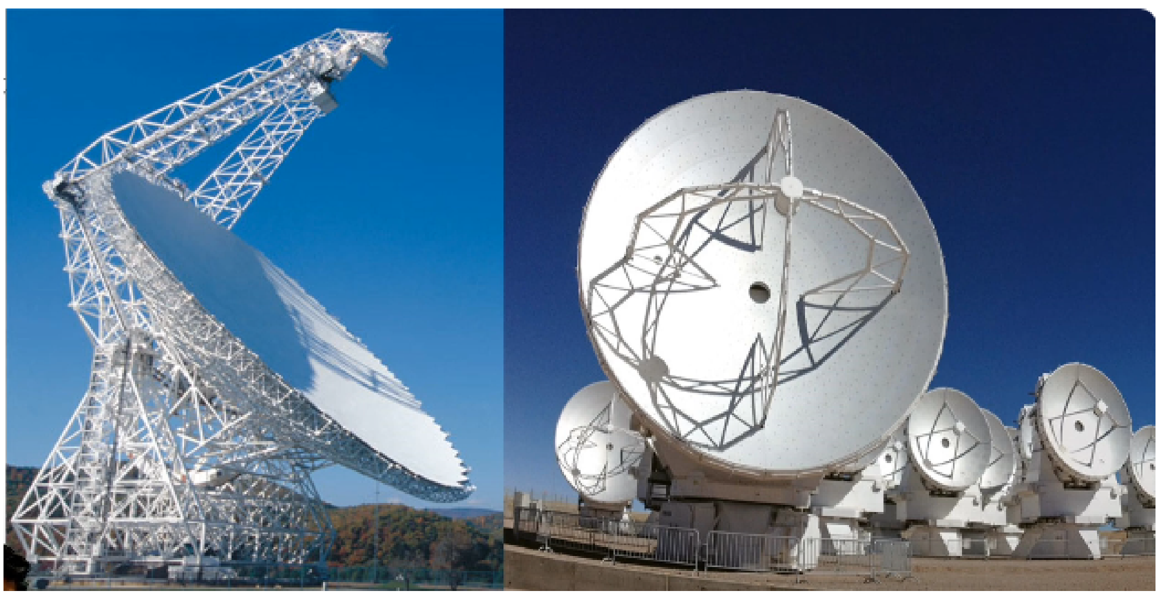
We touch on something called Reciprocity Theorem. We introduce the concept of antenna temperature. Remember last week we discussed about the brightness temperature. So indeed this is definitions of different temperatures of different elements this course will be going through. And then we end this week with different types of antennas, the pros and cons, etc.

Last week we covered how radiation happens, what are the different mechanisms of radiation, thermal, non-thermal. We have not gone in details. That details will come towards the end of this course. But we showed like what is a black body radiation, how in the limit of religions, how do we define brightness temperature and so on and so forth. We also defined several important quantities like flux, intensity, the brightness and what are the relationships among them.

Which one depends on the distance from the source and which one doesn't. We also learned how radiation interacts with the medium at a microscopic level. Now from the first two weeks of lectures, we can safely conclude the following. A charged particle is accelerated, radiation will occur. In other terms if energy of the charged particle is varied with respect to time, it will cause radiation.

An object heated or object with a temperature will generate radiation. So this provides a preliminary understanding on how stars radiate, how radiation might interact with the interstellar or interplanetary medium or even atmosphere. If something radiates in the radio band, we would likely to study it, we will need some kind of a detector. This is where antenna comes into the picture. So if a particular object is radiating in radio band and you have to create a detector which also operates in the same band.

So we have to try to make a detector which is not only sensitive but also has an efficiency to detect and absorb radio waves at a particular wavelength. This week we'll focus on of antenna fundamentals and different kinds of detectors used in radio astronomy.



So this is like in the left hand side you can see this the picture of Green Bank radio telescope. It's a hundred meter in diameter and all the rays typically comes from the sky. It hits the surface of the dish, gets reflected and meets at this location where all the antennas are kept and the receivers.

So this is about the most mostly the assembly of this this but this reflector is a passive reflector. That means it does just simply reflects, doesn't add to the signal magnification or amplification. So same thing this is on the this side right side of the slide you see Alma dishes. Alma is an array in in Chile, operates at a very high radio frequencies and then also you can see a very smooth dish and another reflector at the center at the focus and then it goes below and the receivers are kept near within this hole center of the dish. So all the receivers antenna receiver system are kept below the dish and it gets to this particular central hole.

Now so this big dish is massive but at the end what remains on that on those on the receiving system starts with an antenna. Very basic antenna is the dipole antenna. You have the wires and it bend it 90 amp up and equal to that it forms a dipole antenna. The simple radials monopoles are also used.

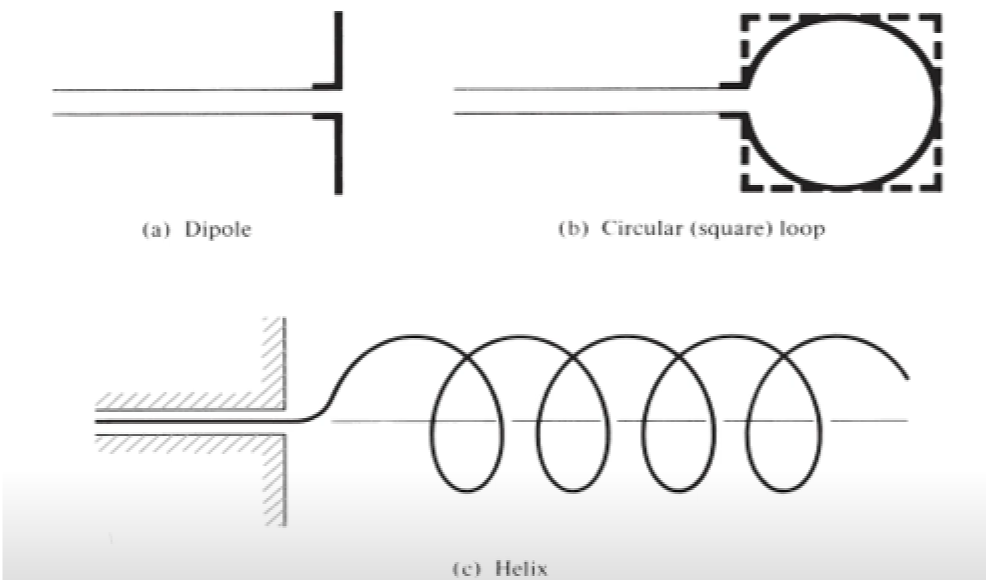


Figure 1.3 Wire antenna configurations.

Simple circular loop antenna also can be used. Helical antenna can also be used. These are all category of wire antennas okay. There can be also planar antennas like in different in 3d geometry. This is the pyramidal horn. This is conical horn and the rectangular waveguide.

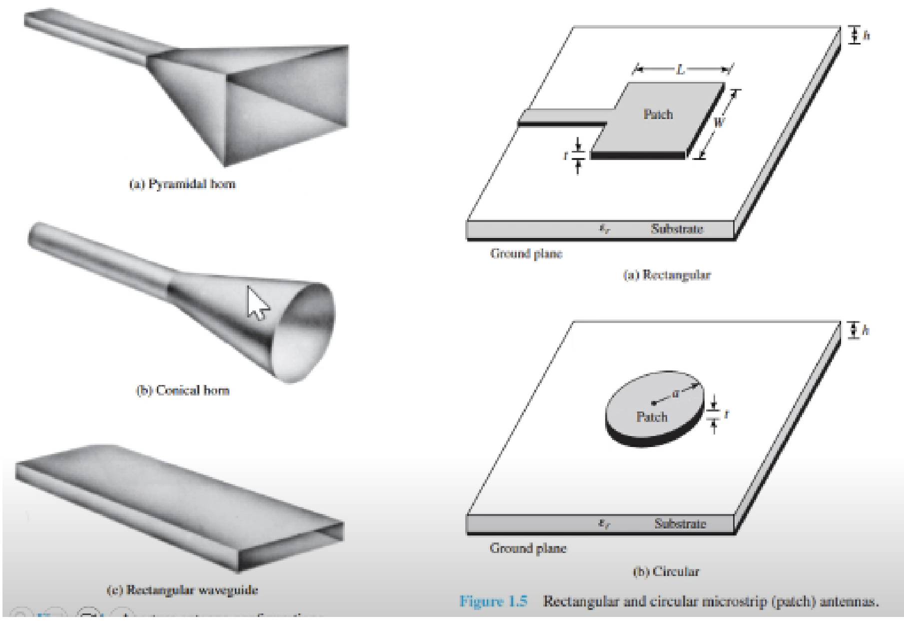


Figure 1.5 Rectangular and circular microstrip (patch) antennas.

All these class the wire antenna and this aperture antenna are all kind of they are the dimension of them are proportional to the radiation wavelength kind of. We will come to that derivation soon. We have another class of antennas which are called rectangular or circular patch antennas and here what happens is the dimension matters but also the substrate in between also matters. It's a dielectric constant matters will determining the wavelength of radiation okay. So we'll come to all of this discussion at much more greater detail through the next few lectures.

I introduced them before because just to make the set the stage so that we can discuss in context. So now what is a radio antenna and why do we need it? Antenna we can term it as a transducer. What is a transducer? It basically converts one form of the energy to the other. What does antenna do? Antenna has two different modes of operation. It can operate in a transmit mode or a receive mode.

In a transmit mode it converts electrical energy into electromagnetic radiation. In the receive mode it operates in a vice versa mode. That means it receives the radiation and converts it to the electronic voltages. Okay so that's why antenna is the most important you know receiving element for radio telescopes okay. Antennas are indispensable for the today life for academia companies government and society apart from radio astronomy.

Antennas are everywhere in mobile phones in cars vehicles aircrafts radars FM radios satellite rocket missiles telescopes etc. If you remember in the first week or second week we have emphasized on the huge development of radars during the World War two which led to this you know quite a huge catalyze catalyze the development of radio astronomy across the world because the radars were not used after the World War and so all the big dishes kind of became a big impetus to start radio astronomy. So that's the thing yeah but apart from radio astronomy antennas are used for other more day-to-day life applications like communication mobile communication satellite communication any form of communication even we can get signals back from satellites for different observations through antennas there's a ground station which major part of the antenna. We mentioned about this all the contribution of Hendrik Arzt Guillermo Marconi and Professor JC Bose for the initial pioneers of this domain but without radio antennas the radio astronomy wouldn't have been possible. What are the other areas where antenna becomes a bit important like communication as I said it serves as a backbone of modern communication enabling seamless connectivity in various sectors.

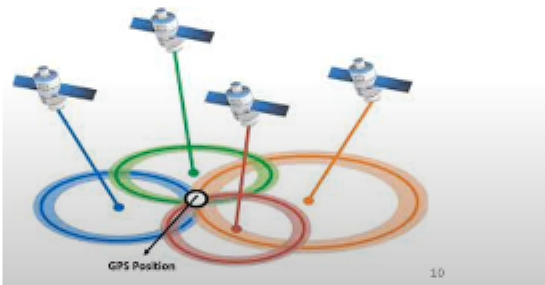
In aviation, maritime industries antenna facilitates critical communication for aircrafts and ships ensuring safe and efficient operations antennas in cellular phones wireless devices keep us connected to friends family and digital world driving global information age. Space probes, radio telescopes for space exploration equipped with arrays of antenna space probes have embarked on missions to explore planets within our solar system and venture into depths of interstellar space. Any communication satellite communicates to the ground station using antennas okay so it doesn't matter I mean what what particular wavelength the actual data has been taken whether it is remote sensing satellite which is observing at different bands visible to radio. If it is looking into the space there are UV telescopes extra telescopes gamma ray telescopes but when it comes to send the information back to the earth they do follow communication channels which operates in radio wavelengths. So now we come to the main application of radio antennas in telescopes.

Radio antennas have been well in use from millimeter wavelength down to meter wavelength in radio telescopes for ages. They capture very faint signals from distant cosmic sources like galaxies, galaxy clusters, black holes, surroundings of course and talks tells us about details of the origin of the cosmos how it is evolving and how the very primordial galaxies evolved till the galaxy to the galaxy we see today and all those features are captured in radio telescopes operating at different wavelengths. The each radio telescope is state of the art and as we move from the older generations to newer and finally to the square kilometer array each of them are really engineering marvel in its own account. So that's a very potent use of radio antennas in radio telescopes radio astronomy. Apart from that we also have radio antennas being used for navigation.

Image courtesy: NCRA, TIFR, GMRT

Image courtesy: Danielle Futselaar

Image courtesy: SKA

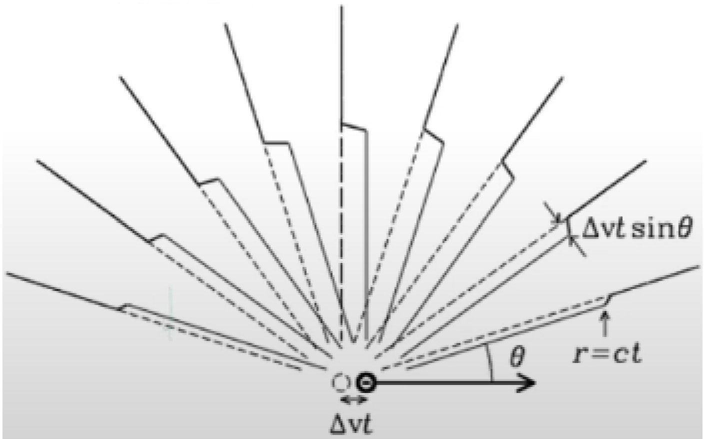


Nowadays we rely heavily on Google Maps for our own travel from one place of the city to another place but the same GPS is also used by by aircrafts, ships by everything else to determine the position of where we are. So GPS is one of the big constellation for that but in general it is called GNSS global navigation satellite system and under that India has its own constellation called Navic and so that also operates in very much in the L and the S band somewhere near one to three gigahertz. So that also falls well between this radio wavelengths and that's another application which very much depends on the nature of the antenna and its operations.

So before we go further next step we should take is understand a little bit more about antenna fundamentals how it radiates what are the basic parameters etc etc. So we know about Maxwell's equations we've already seen those in the in the first week.

- Recall the first week of lecture – Maxwell's equation – we have
$$\nabla.\boldsymbol{H} = 0; \quad \nabla.\boldsymbol{E} \propto \rho; \quad \nabla \times \boldsymbol{E} \propto {}^{-\partial \boldsymbol{H}}/_{\partial t}; \quad \nabla \times \boldsymbol{H} \propto \boldsymbol{J} + \boldsymbol{D}$$
- Wherein, ρ and $\boldsymbol{J}$ are the source term charge density and current density and D .
- So, if there is no source then $\nabla \times \boldsymbol{E} \propto {}^{-\partial \boldsymbol{H}}/_{\partial t}$; $\nabla \times \boldsymbol{H} \propto \boldsymbol{D}$; Thus, if we have a time varying field the fields can self sustain itself.

What we want to revisit the part where how the charge radiates accelerated charge radiate. Now we draw an analogy to the antenna system where antennas are basically like a simple transmission line but moment you start bending the transmission line where there is an abrupt change in the you can say resistance or you can say it's terminated finally the charges can decelerate causing radiation. So you can imagine the dipole antenna is kind of like the extreme version of this bent transmission line.



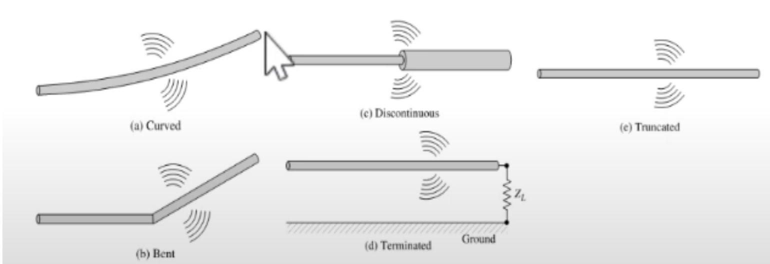


Image courtesy: Antenna Theory By C. Balanis

Okay we come back to a little bit more in the next slide.

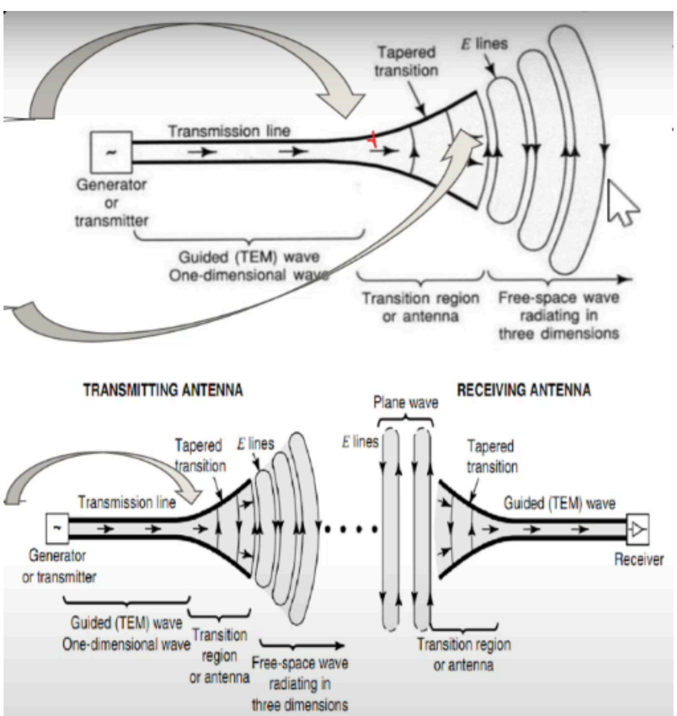


Image courtesy: Antenna Theory By C. Balanis, Antennas and Wave propagation By Kraus

So this transmission line the current was flowing and it starts bending so the field lines keeps on you know curving stretching and finally at the end it cannot stretch anymore so it can detaches from the from the radiating body due to the free space and that's how communication starts happening.

So this this is a very basic structure of the the antenna and so imagine to a parallel plate conductor we have e lines e field lines within it. If you open up that and start bending it that's how this field line starts stretching. Now if there is an alternating source there will be a forward and reverse field and with respect to time the alternating field will be pushed forward and it will stretch at the termination of the wire that's what happens in this particular figure over here. Now thereafter a time there will be a time when the field will leave the wire and pair itself with the upcoming reverse field making a complete loop that's how the stretching gets into extreme point and finally it closes and the field passes on and gets transmitted in the free space. Okay so if you look at the the bottom explanation illustration you can see there's a transmission transmitting antenna and which because of this bending it starts stretching the electric field lines finally that electric field lines closes the loop and detaches from the radiating body and goes into the free space.

On the other side you can imagine a receiving antenna exactly working on the reverse principle. It sees the plane wave coming in, why plane wave? Of course there looks not exactly plane wave but if they transmit through a very long distance they become plane wave and finally when it comes it starts through this transition again from this plane wave to this tapering transition finally guided to the to the transmission line and finally gets into the receiver. Okay that's kind of the entire illustration from a transmission to reception. The same thing happens in in satellite communication. You have one on the on the satellite and one in the ground station.

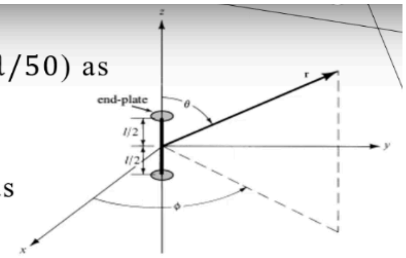
From satellite it basically starts transmitting and the ground station it starts receiving. Now as per the Maxwell's equation the curling e field will generate time varying H field and H field will generate if you they're making a self-sustained electromagnetic field. That's the basic how this radiation actually happens. This picture really is important and this pictorial depictition is very powerful to understand what exactly takes place. Let's step back a little bit and I understand from the point of view a very idealized dipole and what is how the radiation is taking place.

Consider infinitesimal linear wire ($l << \lambda$ or at least $\lambda/50$) as shown in Figure (a) on the right.

Let the cross section of the wire be negligible.

Assume a spatial variation of the current be constant as

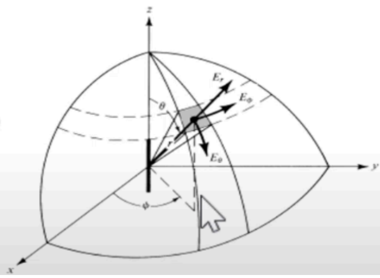
$$\mathbf{I}(z') = \hat{\mathbf{a}}_z I_0 \qquad I_0 = \text{constant.}$$



(a) Infinitesimal dipole

Thus, we can write Vector potential as

$$\mathbf{A}(x, y, z) = \frac{\mu}{4\pi} \int_C \mathbf{I}_e(x', y', z') \frac{e^{-jkR}}{R} dl' \qquad \mathbf{I}_e(x', y', z') = \hat{\mathbf{a}}_z I_0$$



For infinitesimal dipole the source location will be $x' = y' = z' = 0$ and (x, y, z) is the observation point.

So this is textbook example. Consider infinitesimally linear wire where the L is very very less than the lambda. Lambda is the wavelength of radiation. So you have a length of L the half of that length is above this XY plane and half of it is below XY plane. So L by 2 above and L by 2 below along the Z axis and you have a current flowing through along this Z axis an alternating current. So I of Z is given by I naught which is constant times AZ.

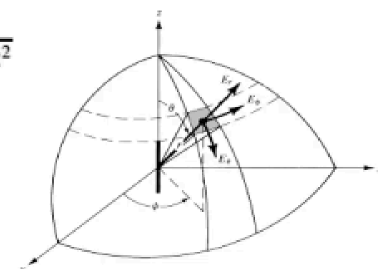
Thus, $R = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2} = \sqrt{x^2 + y^2 + z^2}$

$= r = \text{constant}$

Therefore, $dl' = dz'$.

Thus, we can rewrite the vector potential as

$$\mathbf{A}(x, y, z) = \hat{\mathbf{a}}_z \frac{\mu I_0}{4\pi r} e^{-jkr} \int_{-l/2}^{+l/2} dz' = \hat{\mathbf{a}}_z \frac{\mu I_0 l}{4\pi r} e^{-jkr}$$


Electric field orientation

By use of cartesian to spherical conversion we get

$$A_r = A_z \cos\theta = \frac{\mu I_0 l e^{-jkr}}{4\pi r} \cos\theta$$

$$A_\theta = -A_z \sin\theta = -\frac{\mu I_0 l e^{-jkr}}{4\pi r} \sin\theta$$

$$A_\phi = 0$$

Okay so that is going in and so you can write the vector potential A in terms of I this is already you know you know from the previous past the first week that you can write if you have current density you can write the corresponding a vector potential in this form and so you can write this. So now the A in terms of Cartesian coordinate is expressed but we see this is a very basically space very spherical symmetry exist in the system so we would like to express it more in the spherical polar coordinate. So you can redefine the R which is any distance from this origin and you can see you can recast A from the original point so A from the previous slide previous version is integral of this where I XYZ is equal to just I naught AZ. So you just have one component along the Z axis and so you finally get this is your mu I naught L over 4 pi R e to the power minus J k R and on the Z axis is your vector potential. Now if you want to convert it through the spherical coordinate then A has R and the theta component the azimuthal component is equal to 0.

So you have two components instead of just one along Z in this Cartesian coordinate case. So if you if you know A you can derive H and if you know H then you can derive E from there we have done this in the in the first week of the lecture go back to those slides and try to derive by yourself there is a transition given if you know A the vector potential how to derive H and then finally from H to E okay.

Thus, the magnetic field associated with the vector potential is

$$\mathbf{H} = \hat{\mathbf{a}}_\phi \frac{1}{\mu r}\left[\frac{\partial}{\partial r}(r A_\theta) - \frac{\partial A_r}{\partial \theta}\right]$$

Thus, from above equation and Maxwell's equation we have ($J = 0$ as current is constant spatially).

$$H_r = H_\theta = 0$$

$$H_\phi = j\frac{kI_0 l \sin\theta}{4\pi r}\left[1 + \frac{1}{jkr}\right]e^{-jkr}$$

$$E_r = \eta\frac{I_0 l \cos\theta}{2\pi r^2}\left[1 + \frac{1}{jkr}\right]e^{-jkr}$$

$$E_\theta = j\eta\frac{kI_0 l \sin\theta}{4\pi r}\left[1 + \frac{1}{jkr} - \frac{1}{(kr)^2}\right]e^{-jkr}$$

$$E_\phi = 0$$

So these are the different shapes this thing takes in the spherical polar coordinate. Now let us imagine the implication of different values of R. R was the distance from the center of the origin to the any distance okay.

Now as the if you look at the E as R goes to infinity the ER actually is varying as 1 over R square the radial component of electric field. So as R goes to infinity E phi is already 0. So ER actually goes to 0 because 1 over R square becomes a very small number negligible number almost going to 0. So as R tends to infinity 1 over R square terms goes to 0. So ER vanishes so only portion which stays is the E theta.

Implications at large distances as r $\rightarrow \infty$

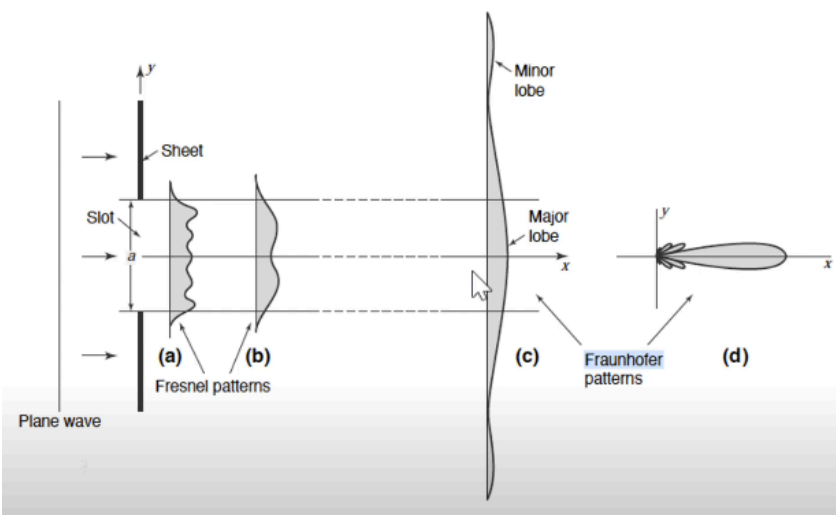
- E_r varies with $\frac{1}{r^2} \rightarrow$ for larger distance $E_r \rightarrow 0$; only E_θ survives.
- The terms $(1/jkr^2 - 1/k^2r^3)$ will vanish from E_θ and the term $1/jkr^2$ will vanish from H_ϕ.
- Thus at large distances the E and H field will become transverse to each other. That means the EM field changes to radiating field.

At small distances -

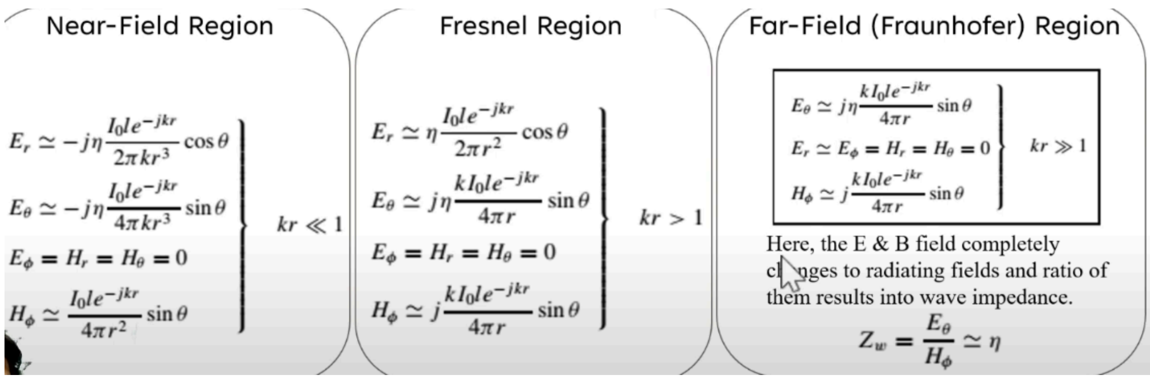
- The E field is more dominant than the H field.
- Also, the maximum contribution to the field is due to imaginary parts of the field's equation.
- Thus, we can say that it is acting more like a capacitor.

So E theta also has 1 over R square and 1 over R so the first term of the that one will remain and the next terms will also vanish. That simplifies a lot. So 1 over yeah so if you have the first one in the denominator has R so multiplied by 1 is 1 over R but 1 over R square and 1 over R cube terms vanishes so only 1 over R terms remains. The first term in this expansion of E theta survives the remaining two disappears ER disappears E phi disappears already equal to 0.

So that's the simplified version. Similarly if you look at the H phi component HR and HT theta are equal to 0 already there also the second term 1 over R square goes to 0 so only the first term remains they become much simpler in the expression. At small distances the E field is the more dominant than the H field. There also we can infer from here if you look at the above two boxes and the maximum contribution of the field is due to imaginary parts of the fields equation. Thus we can say it is acting more like a capacitor having more reactive component. Now based on the value of R we also define three different zones at the nearby there is a Fresnel zone the reactive near field reactive zone then intermediate zone and then finally the far field or the distance zone.



Okay putting into the antenna into context so you can see the reactive near field from the aperture of the antenna till lambda over 2 pi and from lambda over 2 pi to do 2d square over lambda this is the radiating near field of Fresnel zone and from 2d square anything above is called far field or front of a zone. We will come again in details when we study radiation patterns in more detail.



For now that's the that's the particular three regimes Kr very very less than 1 greater than 1 and much greater than 1 at the very far field. So you can see this what the approximations this particular fields takes place at the three different regimes. Please note that when in the far field regime the electric and magnetic field completely changes to radiating fields and the ratio of them becomes the wave impedance.

Okay that is the requirement. So before we close this particular lecture we go through a couple of example questions like before so that the understanding becomes a bit more clear. What which of the following is true for a Hertz dipole? The length of the antenna is greater than the wavelength, length of the antenna is less than the wavelength, length of the antenna is equal to the wavelength, length of the antenna is much much less than the wavelength.

1. Which of the following is true for a Hertz dipole?

   a) The length of the antenna >wavelength
   b) The length of the antenna < the wavelength
   c) The length of the antenna = the wavelength
   d) The length of the antenna << than the wavelength

The correct option is (d) the length of the antenna is much lesser than the wavelength and this is already discussed in the assumptions of the Hertz dipole treatment.

Which of the condition is true for front of a region of the Hertz dipole? Kr greater than 1 or very very less than 1 equal to 1 or just greater than 1.

2. Which of the condition is true for the Fraunhofer region for Hertz Dipole?

a) $kr \gg 1$
b) $kr \ll 1$
c) $kr = 1$
d) $kr > 1$

Now the correct option is A of course we just went through the previous slides.

The next example is a Hertz dipole is made with the current element of length 1 millimeter carrying current of 1 milliampere. Find the electric field provided Kr is equal to 1 and R is equal to 1 meter. Assume that the observer is at the elevation of 45 degrees.

3. A Hertz dipole is made with a current element of length 1mm carrying current of 1mA. Find E_r provided $kr = 1$ and $r = 1\ m$.

[Assume observer is located at elevation of 45 degrees]

So we know that the E n, E r takes this expression for this Hertz dipole. So we put all the values theta is equal to 45 degree, Kr is equal to 1, R is equal to 1 meter.

So if you put all of them in the expression you finally get the value of the electric field in volt per meter.

ANSWER

We know that $$E_r = \eta \frac{I_0 l \cos\theta}{2\pi r^2}\left[1 + \frac{1}{jkr}\right] e^{-jkr}$$

Given that

$I_0 = 0.001\ A\ ,\ l = 0.001\ m,\ \theta = 45^o,\ kr = 1$ and $r = 1\ m.$

It is known that $\eta = 120\pi\ \Omega$ then,

$\eta I_0 l cos\theta = 0.000267\ Vm$

$2\pi r^2 = 6.283\ m^2$

$$\left[1 + \frac{1}{jkr}\right] e^{-jkr} = [1 - j]e^{-j} = [1 - j](cos1 - jsin1) = -0.3 - j1.38$$

Thus, Er= $\frac{(0.000267)(-0.3-j1.38)}{6.283}\ Vm^{-1} = -(1.27 + j5.86) \times 10^{-5}\ Vm^{-1}$

That brings us close to this particular segment of the lecture and we'll see you to the next lecture. Before finishing we this is a very standard stuff taken from several different books. So we just acknowledge the references in particular the book by Balanis and Krauss for this antenna lectures particularly has been used. Thank you. See you in the next class.