ECE 3317
Applied Electromagnetic Waves

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Fall 2023

Notes 21
Introduction to Antennas

Introduction to Antennas

An antenna is a device that is used to transmit and/or receive an electromagnetic wave.

The antenna itself can always transmit or receive, but it may be used for only one of these functions in a particular application.

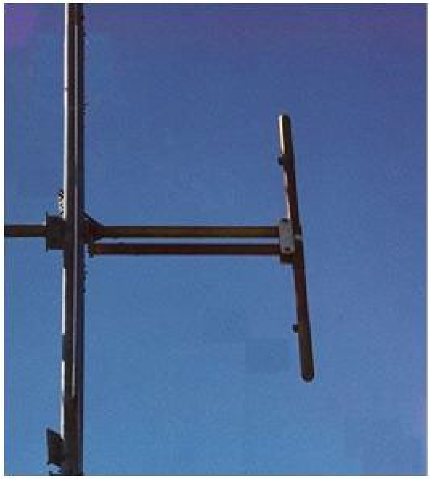
Examples:

- Cell-phone antenna (transmit and receive)
- TV antenna in your home (receive only)
- Wireless LAN antenna (transmit and receive)
- FM radio antenna (receive only)
- Satellite dish antenna (receive only)
- AM radio broadcast tower (transmit only)
- GPS position location unit (receive only)

Advantages of Antennas

Antennas are often used for a variety of reasons:

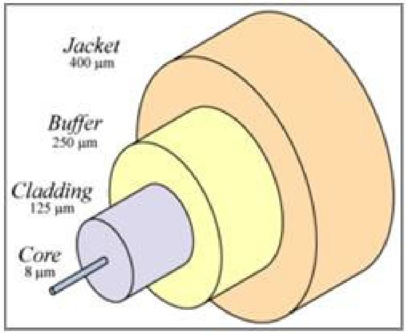
- For communication over long distances, to have lower loss (see next slide)
- Where waveguiding systems (e.g., transmission lines such as coaxial cable or fiber optic cable) are impractical or inconvenient
- When it is desired to communicate with many users at once



Antenna

Coax

Twisted pair (CAT 5 cable)



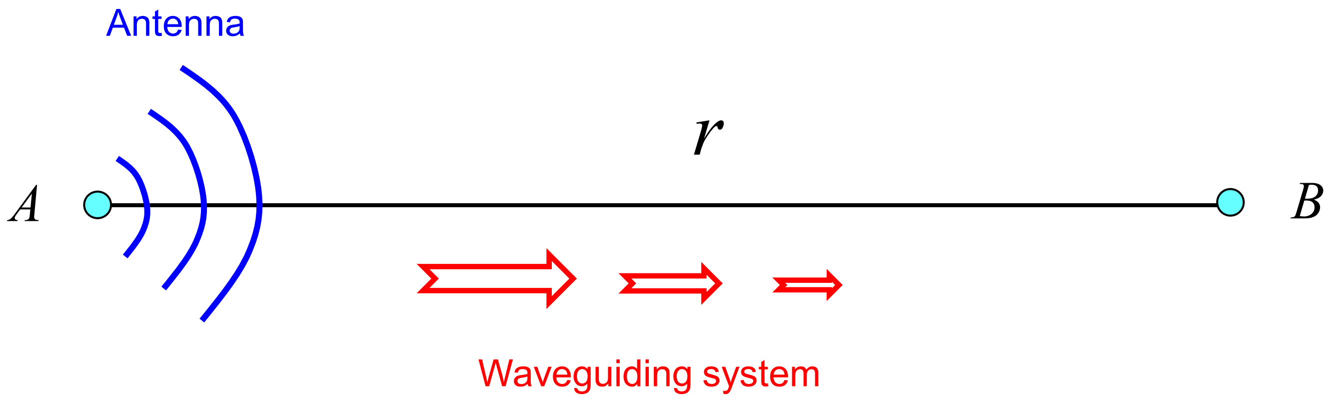
Fiber optic cable

Antennas vs. Waveguiding Systems

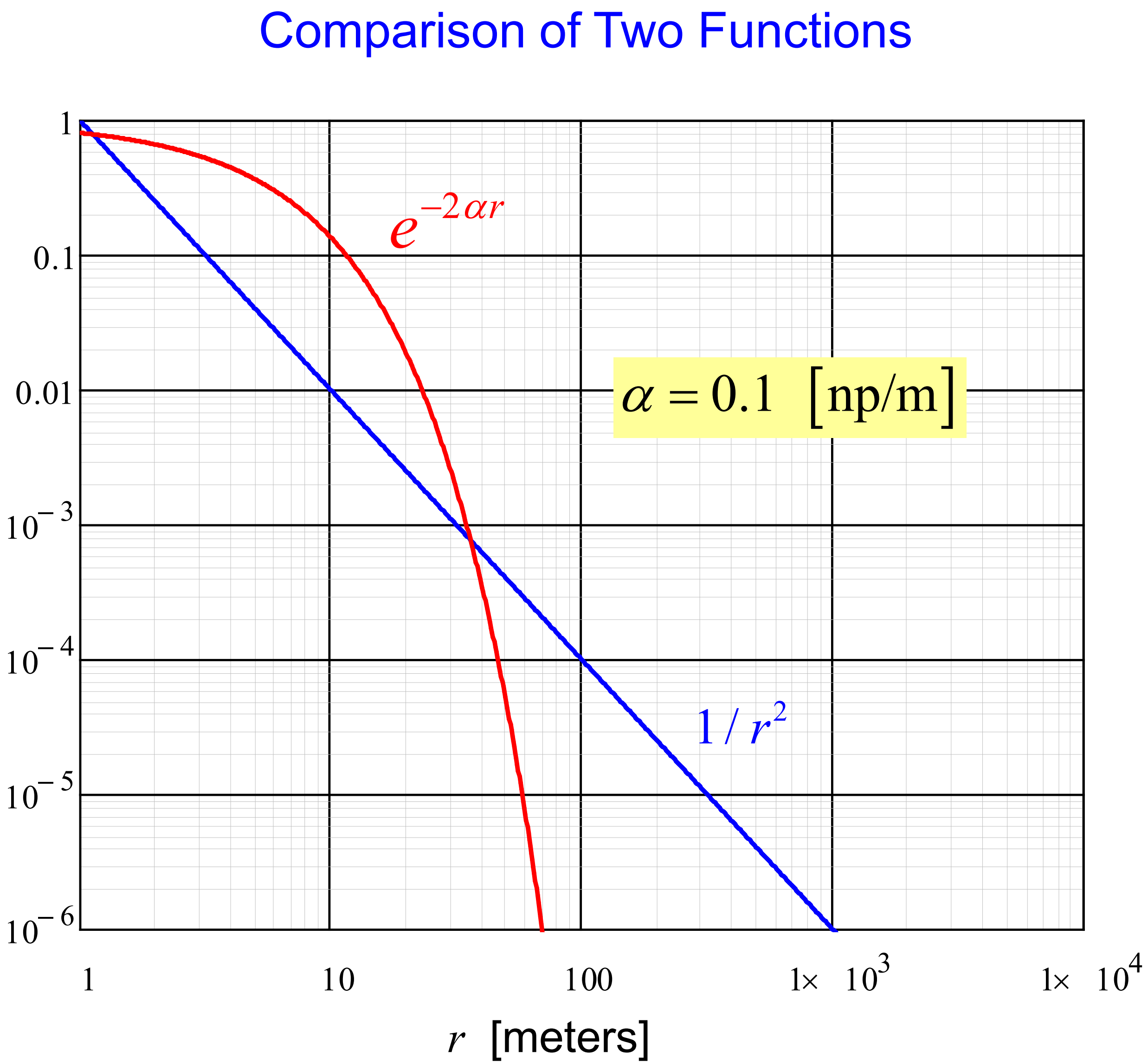
Wireless systems using antennas will always be better (lower loss) than wired (waveguiding) systems for large distances.

Power loss from antenna broadcast: $1/r^2$ $\longleftarrow$ (always better for large r)

Power loss from waveguiding system: $e^{-2\alpha r}$ ($\alpha =$ attenuation constant)



Antennas vs. Waveguiding Systems (cont.)



Comparison of Waveguiding Systems with Wireless Systems

Attenuation in dB 1 GHz

	RG59	Single Mode	Two Dipoles	34m Dish+Dipole
Distance	Coax	Fiber	Wireless	Wireless
1 m	0.4	0.0003	28.2	-
10 m	4	0.003	48.2	-
100 m	40	0.03	68.2	-
1 km	400	0.3	88.2	39.3
10 km	4000	3	108.2	59.3
100 km	-	30	128.2	79.3
1000 km	-	300	148.2	99.3
10,000 km	-	3000	168.2	119.3
100,000 km	-	-	188.2	139.3
1,000,000 km	-	-	208.2	159.3
10,000,000 km	-	-	228.2	179.3
100,000,000 km	-	-	248.2	199.3

Main Properties of Antennas

Main properties of antennas:

- Radiation pattern
- Beamwidth and directivity (how directional the beam is)
- Sidelobe level
- Efficiency (power radiated relative to total input power)
- Polarization (linear, CP)
- Input Impedance
- Bandwidth (the useable frequency range)

Types of Antennas

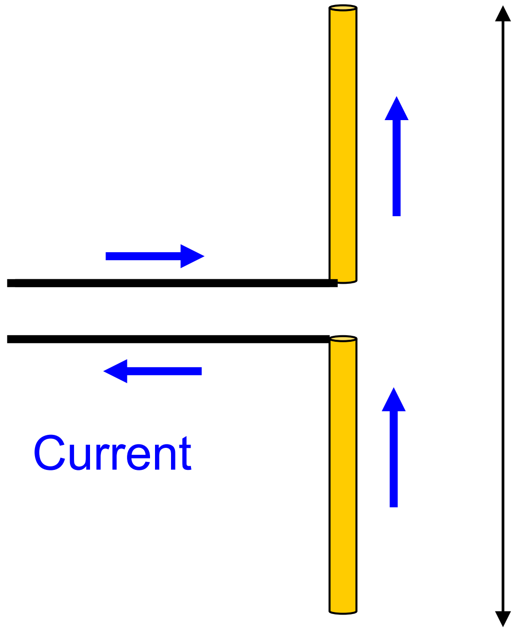
Reflector (dish) antenna

Ideally, the dish is parabolic in shape.

- Very high bandwidth
- High directivity (directivity is determined by the size / wavelength)
- Linear or CP polarization (depending on how it is fed)
- Works by focusing the incoming wave to a collection (feed) point

Types of Antennas (cont.)

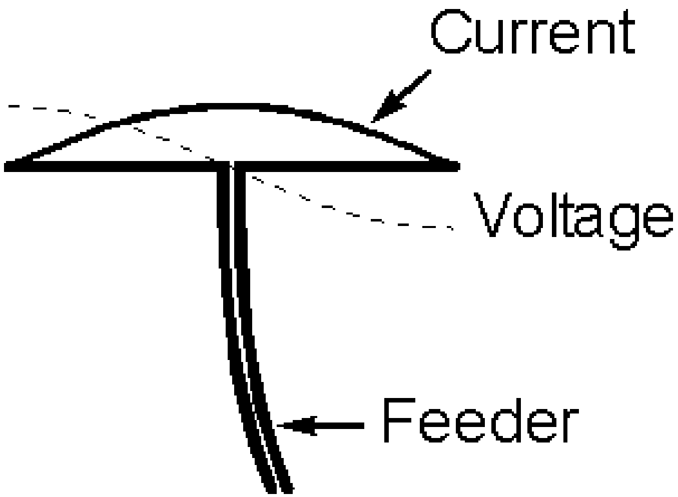
Dipole Wire Antenna



$$L \approx \lambda_0 / 2$$

(resonant)

$$\lambda_0 = c / f$$

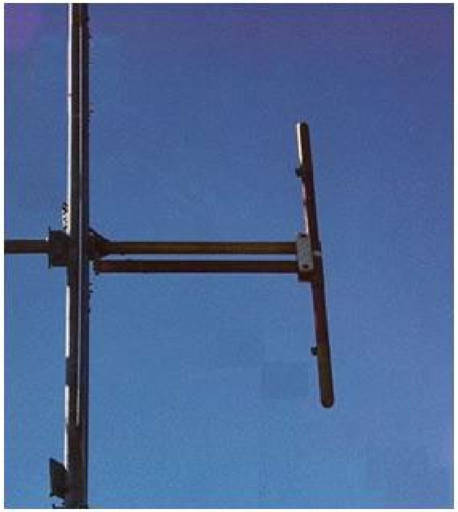


$$Z_{in} = 73 \; [\Omega]$$

- Very simple
- Moderate bandwidth
- Low directivity
- Omnidirectional in azimuth
- Most commonly fed by a “twin-lead” transmission line
- Linear polarization (E_θ, assuming wire is along z axis)
- The antenna is resonant when the length is about one-half free-space wavelength

Types of Antennas (cont.)

Dipole Wire Antenna (cont.)



“Rabbit ears”

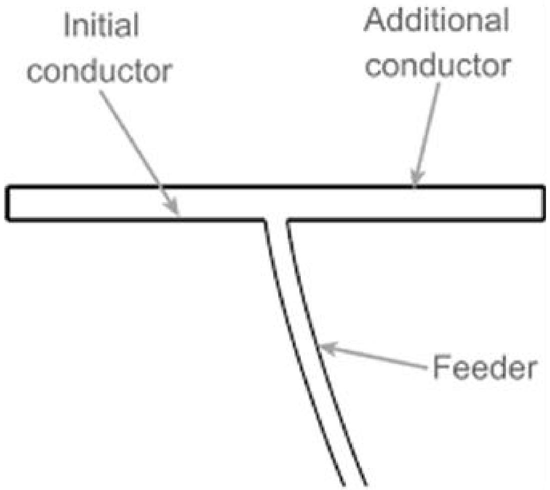
“Bow-tie” variation (for higher bandwidth)

Types of Antennas (cont.)

Folded Dipole Antenna

The folded dipole is a variation of the dipole antenna. It has an input impedance that is 4 times higher than that of the regular dipole antenna.

At resonance : $Z_{in} = 292\ [\Omega]$



Compatible with TV twin lead

$Z_0 = 300\ [\Omega]$

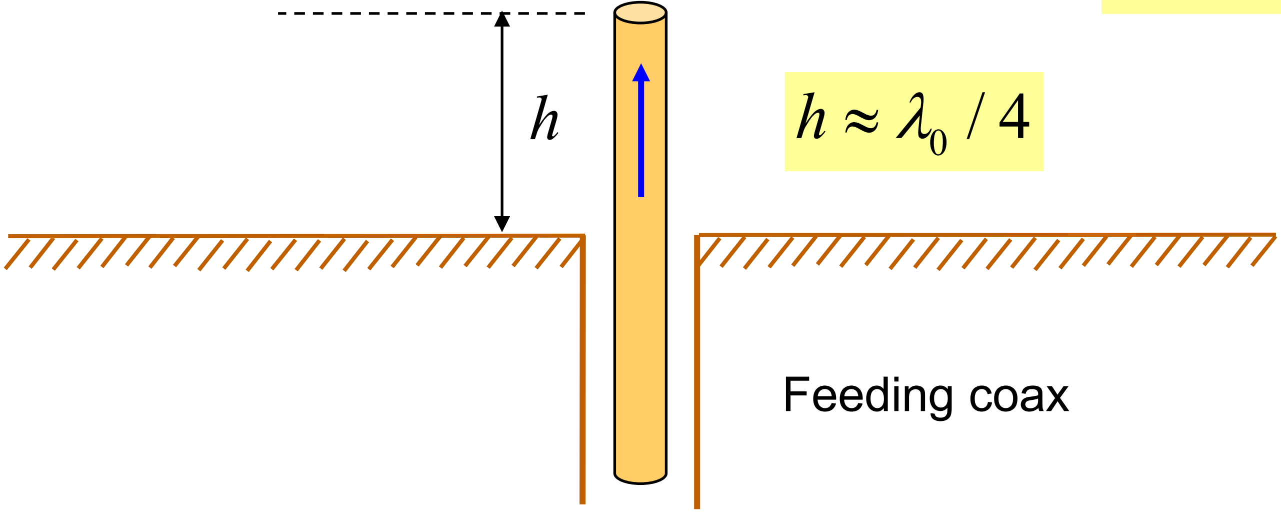
Matched system:

$Z_{in} = Z_0$

Types of Antennas (cont.)

Monopole Wire Antenna

$$Z_{in} = 36.5 \ [\Omega]$$



$$h \approx \lambda_0 / 4$$

This is a variation of the dipole, using a ground plane instead of a second wire.

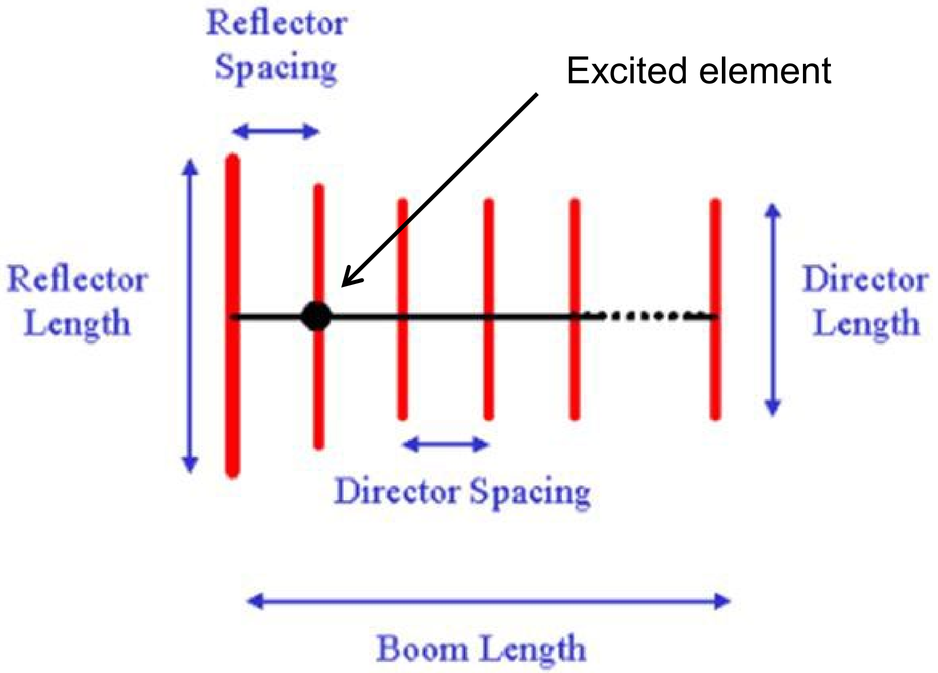
- Similar properties as the dipole
- Mainly used when the antenna is mounted on a conducing object or platform
- Usually fed with a coaxial cable feed

Types of Antennas (cont.)

Monopole Wire Antenna (cont.)

Types of Antennas (cont.)

Yagi Antenna



Prof. Yagi

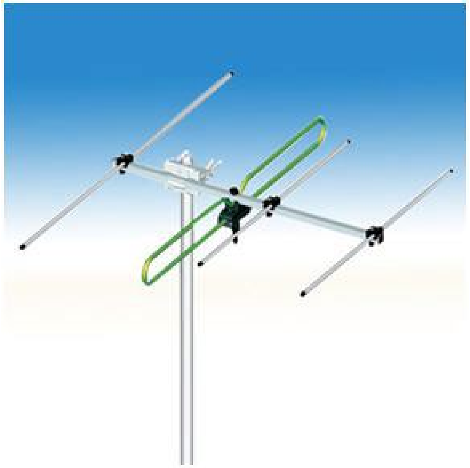
This is a variation of the dipole, using multiples wires (with one “reflector” and one or more “directors” (acting as a lens).

- Low bandwidth
- Moderate directivity
- Commonly used as a UHF TV antenna

Types of Antennas (cont.)

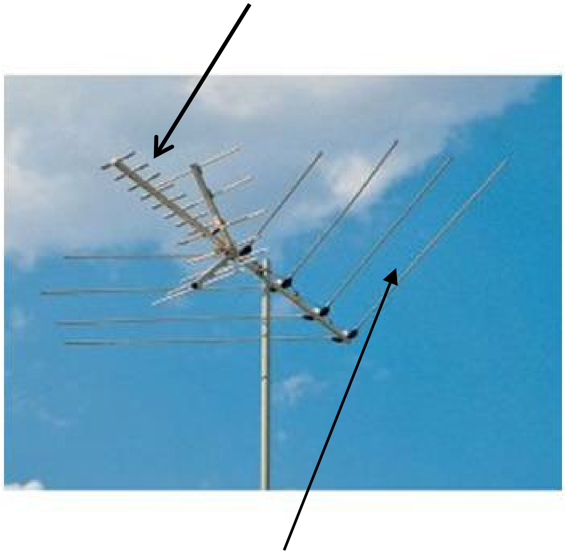
Yagi Antenna (cont.)

UHF Yagi



UHF Yagi

UHF Yagi



VHF Log-periodic

Types of Antennas (cont.)

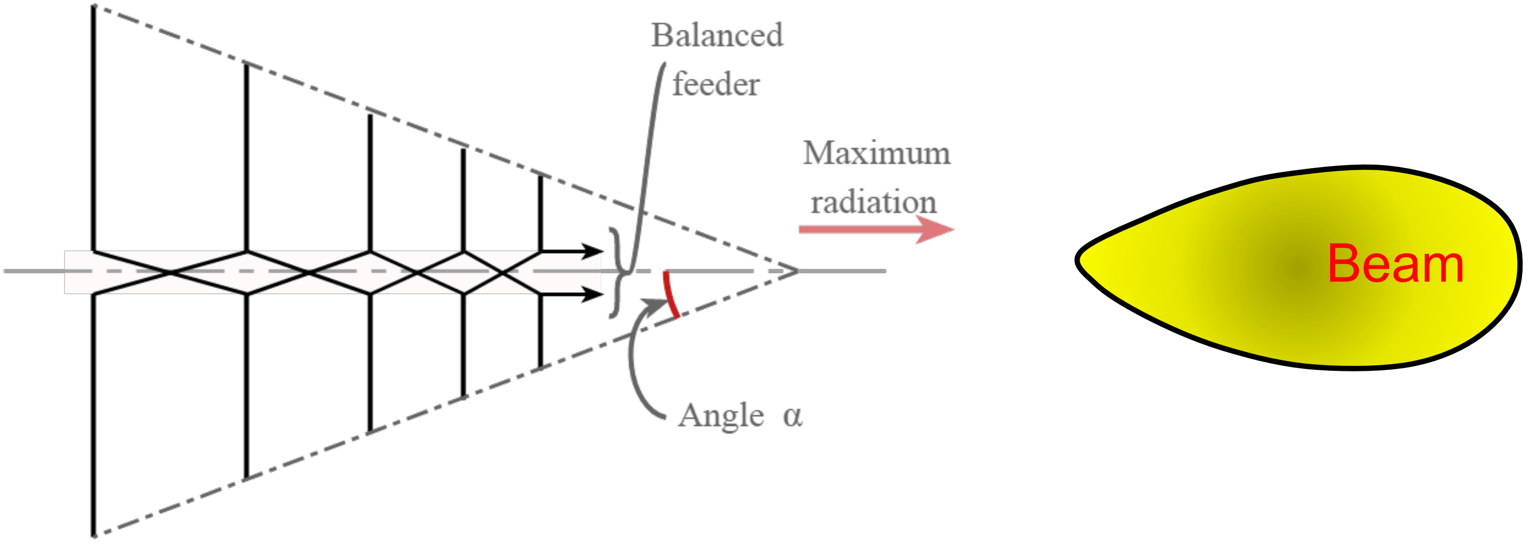
Yagi of CP Elements

Two perpendicular dipoles fed 90° out of phase.

- Used for circular polarization

Types of Antennas (cont.)

Log-Periodic Antenna



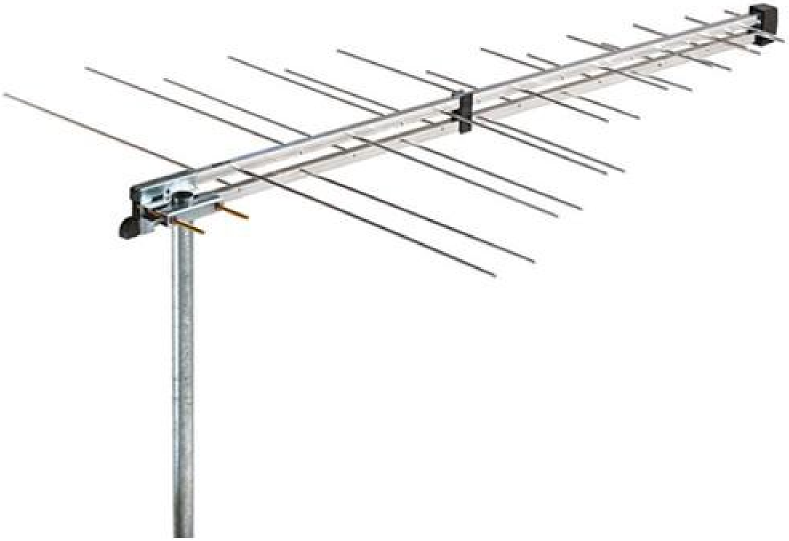
This consists of multiple dipole antennas of varying lengths, connected together.

- High bandwidth
- Moderate directivity
- Commonly used as a VHF TV antenna

The input impedance repeats periodically when plotted vs. the log of the frequency.

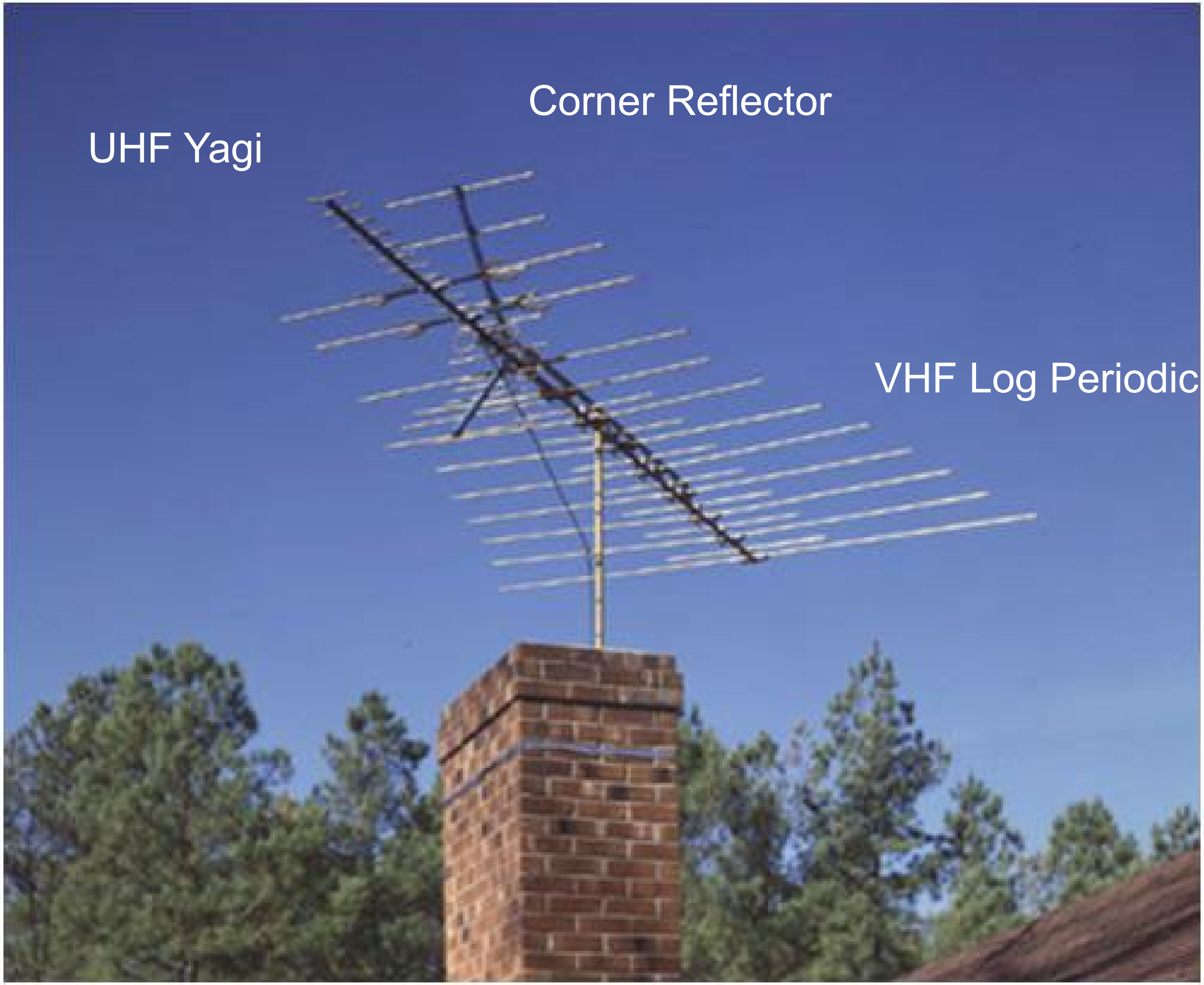
Types of Antennas (cont.)

Log Periodic Antenna (cont.)



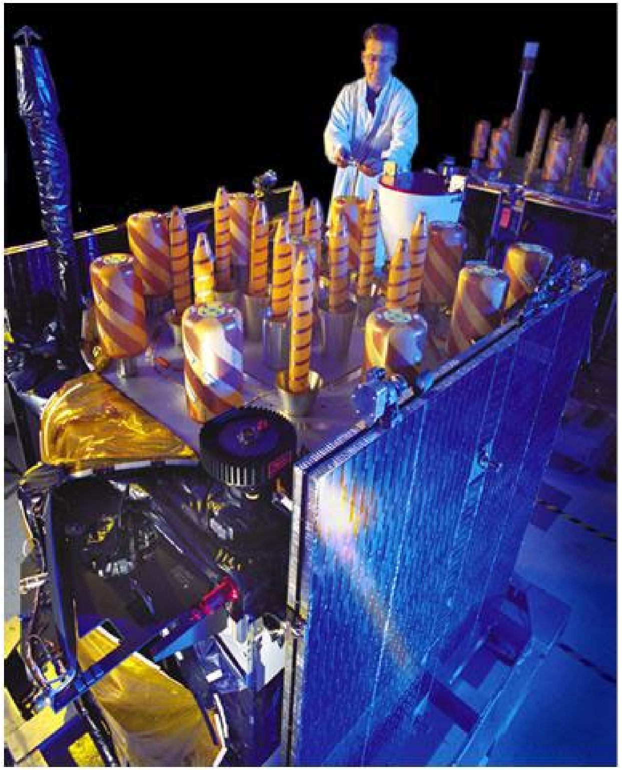
Types of Antennas (cont.)

Typical Outdoor TV Antenna



Types of Antennas (cont.)

CP Helical Antenna

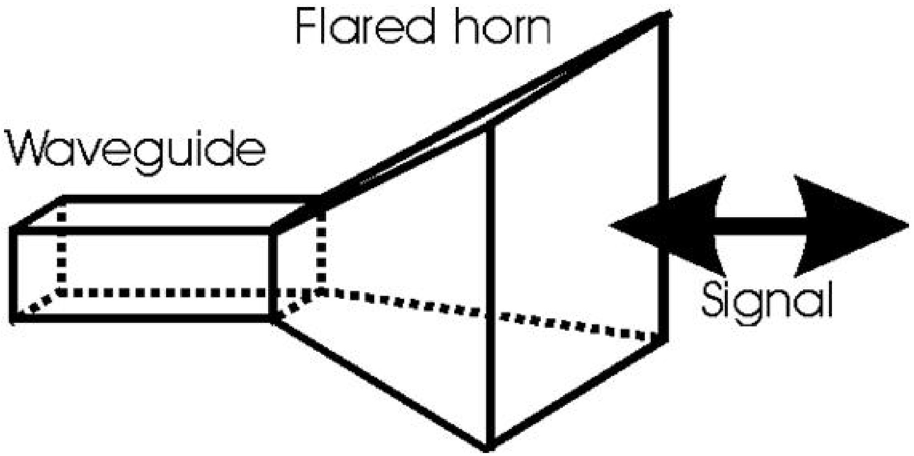


GPS satellite

- ❖ Helical antennas are often used for circular polarization.

Types of Antennas (cont.)

Horn Antenna

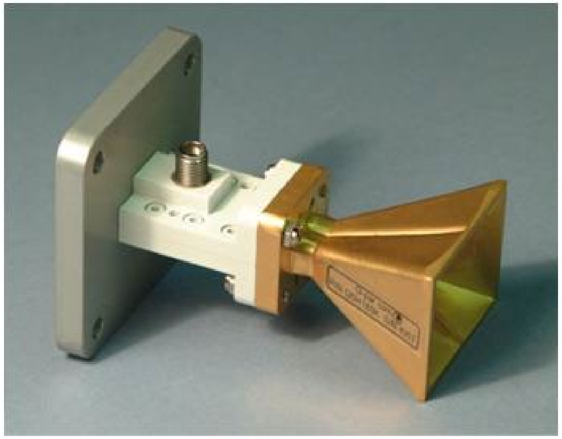


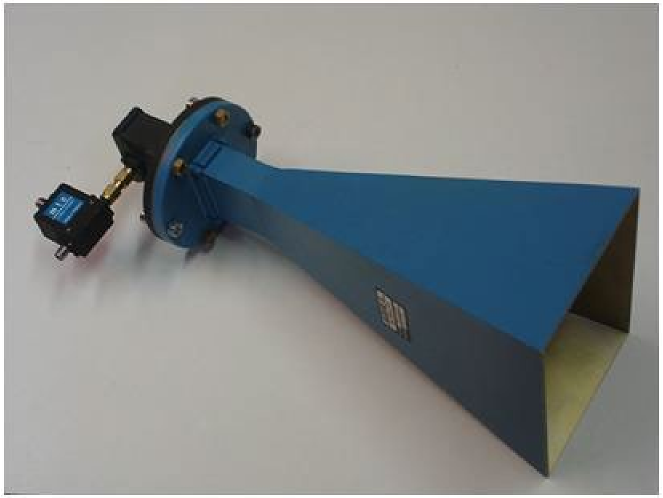
It acts like a “loudspeaker” for electromagnetic waves.

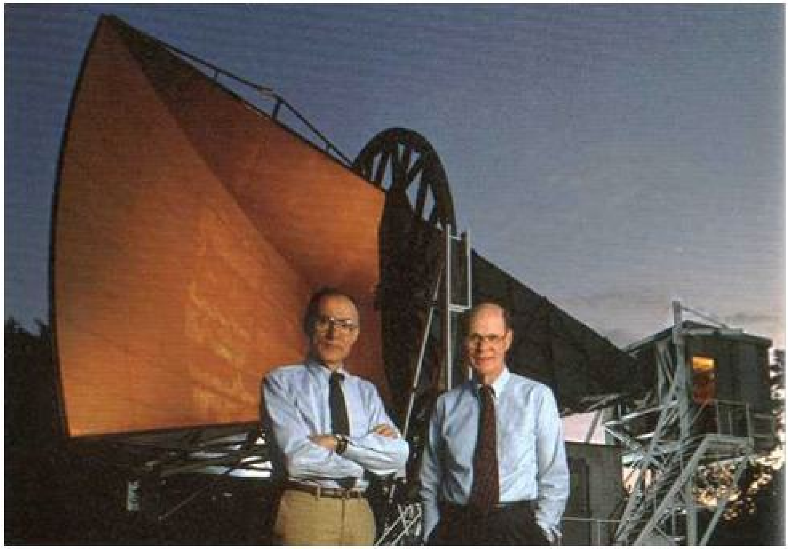
- High bandwidth
- Moderate to high directivity (directivity is determined by the size / wavelength)
- Commonly used at microwave frequencies and above
- Often used as a feed for a reflector antenna

Types of Antennas (cont.)

Horn Antenna (cont.)







Arno A. Penzias and Robert W. Wilson used a large horn antenna to detect microwave signals from the “big bang” (Nobel Prize, 1978).

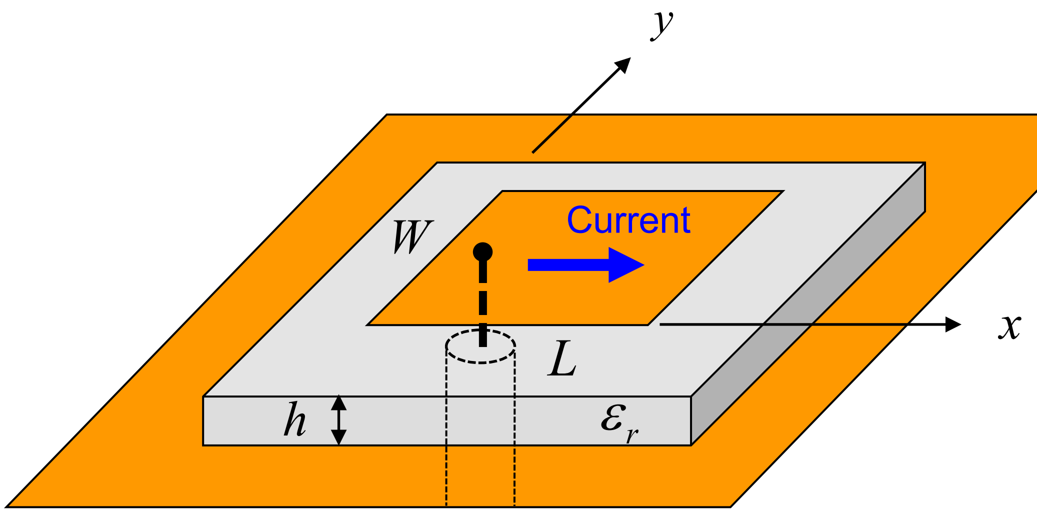
Types of Antennas (cont.)

Horn Antenna (cont.)

This is a variation called the “hoghorn” antenna (a combination of horn+reflector).

Types of Antennas (cont.)

Microstrip (Patch) Antenna



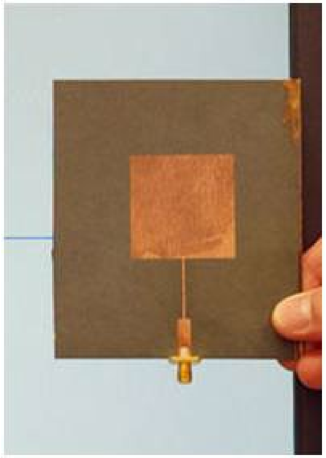
$$L \approx \lambda_d / 2 = \frac{1}{2} \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$

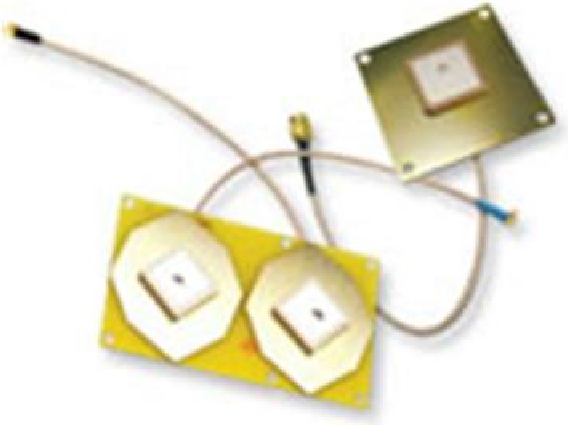
It consists of a printed “patch” of metal on top of a grounded dielectric substrate.

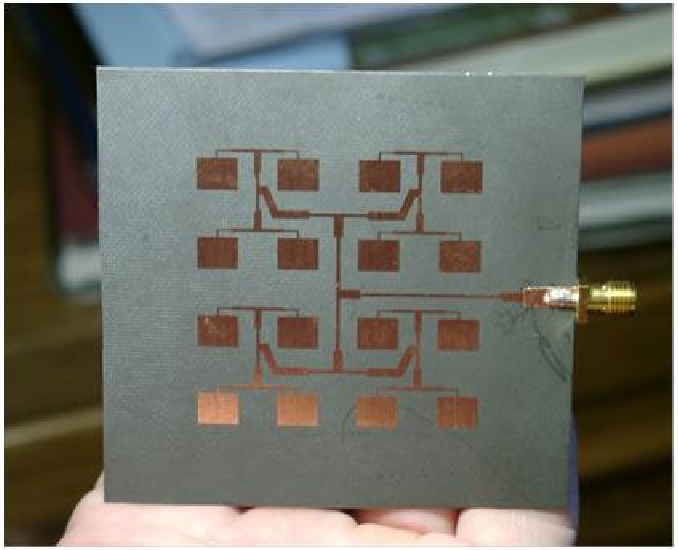
- Acts as a *radiating resonant cavity*
- Easily fed by microstrip line or coaxial cable
- Low to moderate bandwidth (usually a few percent)
- Low directivity (unless used in an array)
- Low-profile (h can be made very small, at the expense of bandwidth)
- Can be easily made by etching or machining
- Can be made conformable (flexible and mounted on a curved surface)
- Commonly used at microwave frequencies and above

Types of Antennas (cont.)

Microstrip (Patch) Antenna (cont.)

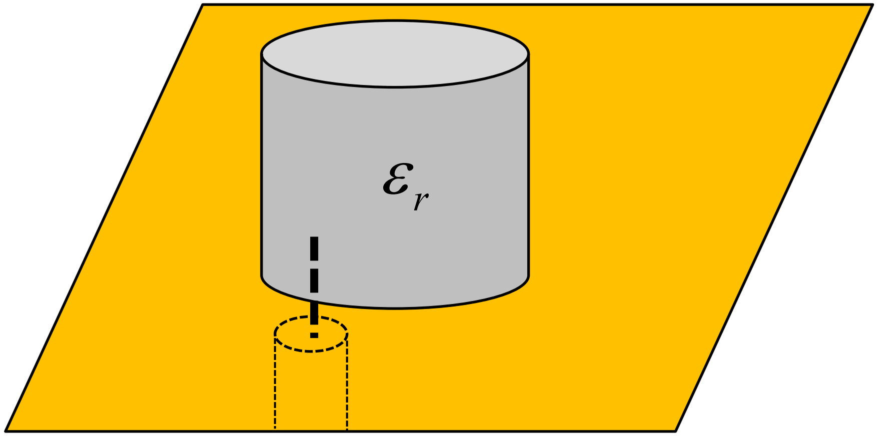






Types of Antennas (cont.)

Dielectric Resonator Antenna (DRA)



Cylindrical DRA

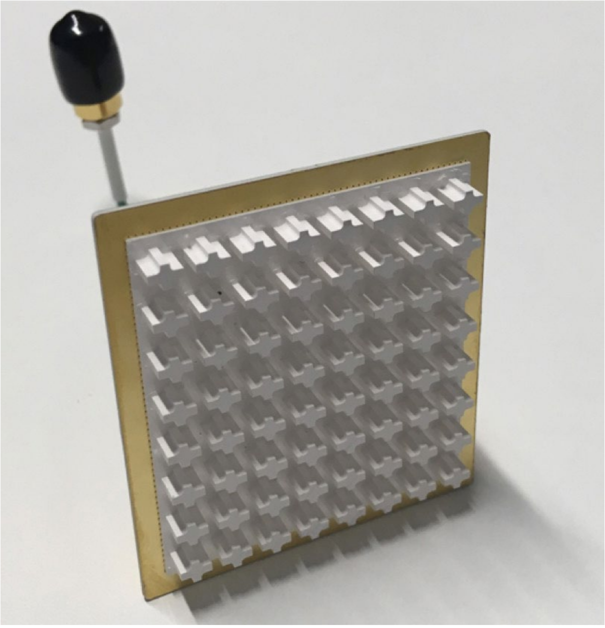
The dielectric resonator antenna was invented by our very own Prof. Long in the Dept. of ECE!

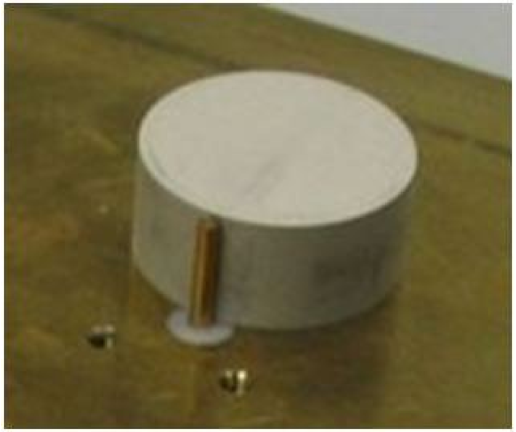
It consists of a dielectric material (such as ceramic) on top of a grounded dielectric substrate.

- Acts as a *resonating dielectric object*
- Moderate to large bandwidth
- Low directivity (unless used in an array)
- Commonly used at microwave frequencies and above
- Usually more difficult to fabricate than a patch antenna

Types of Antennas (cont.)

Dielectric Resonator Antenna (cont.)



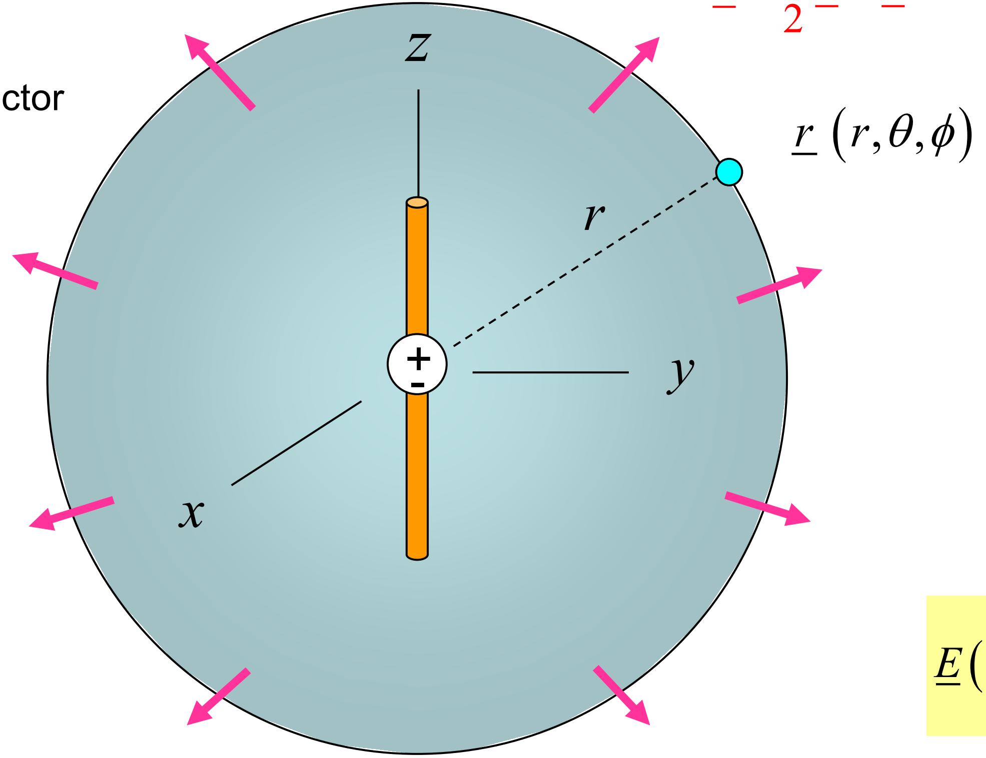


Antenna Radiation

We consider here the radiation from an antenna.

$$\underline{S} = \frac{1}{2}\underline{E} \times \underline{H}^{*}$$

$\underline{S}$ = Poynting vector



"far field"

$$r \to \infty$$

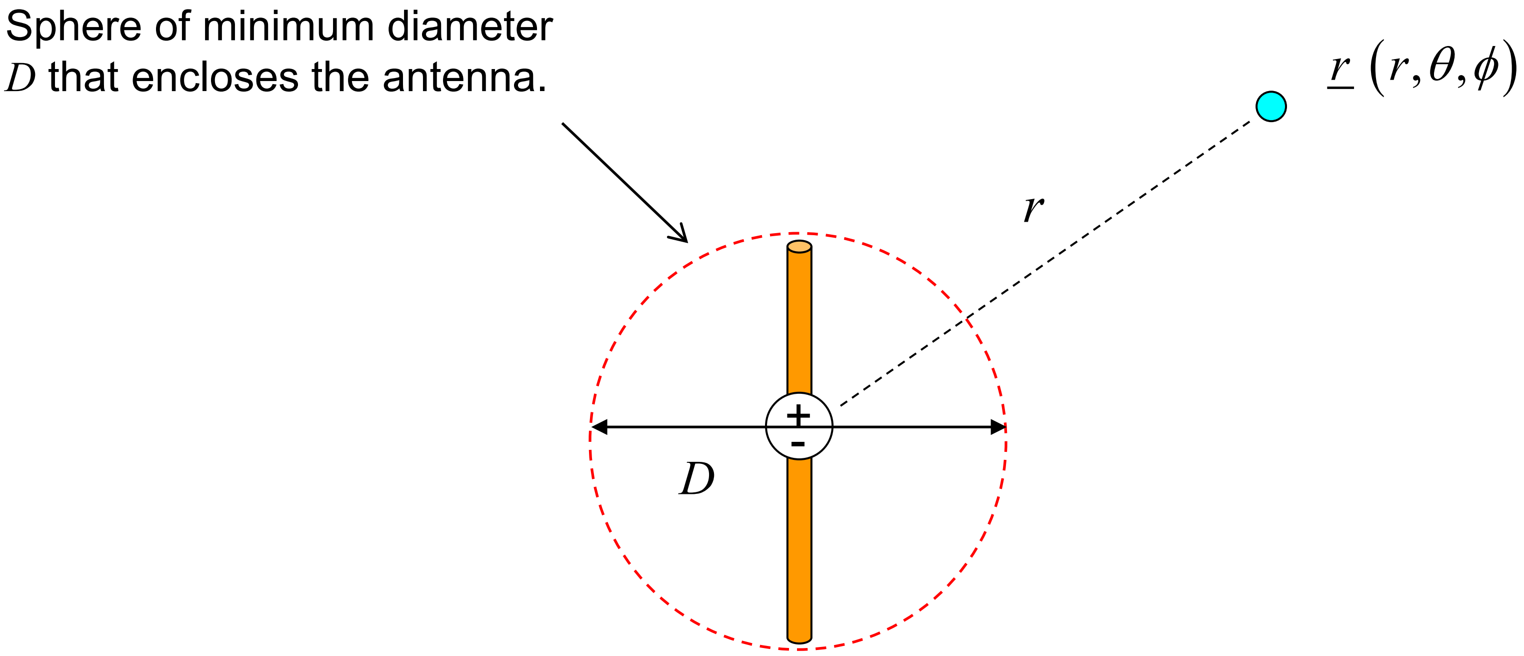
$$\underline{E}(r,\theta,\phi) = \left(\frac{e^{-jk_0 r}}{r}\right)\underline{E}^{\mathrm{FF}}(\theta,\phi)$$

(phasor electric field)

- The <u>far-field</u> radiation acts like a plane wave going in the radial direction.
- The <u>shape</u> of the pattern in the far field is only a function of (θ, ϕ).

Antenna Radiation (cont.)

How far do we have to go to be in the far field?



$$r > \frac{2D^2}{\lambda_0}$$

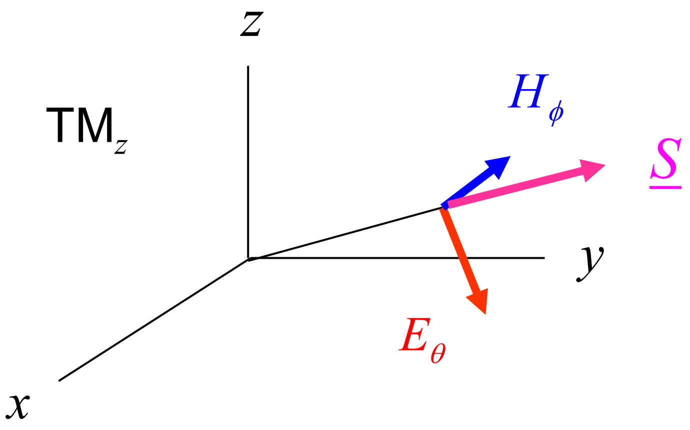
Antenna Radiation (cont.)

The far-field has the following form:

$$\underline{E} = \underline{\hat{\theta}}\, E_\theta + \underline{\hat{\phi}}\, E_\phi \quad \left(\text{phasor electric field vector}\right)$$

$$\underline{H} = \underline{\hat{\theta}}\, H_\theta + \underline{\hat{\phi}}\, H_\phi \quad \left(\text{phasor magnetic field vector}\right)$$

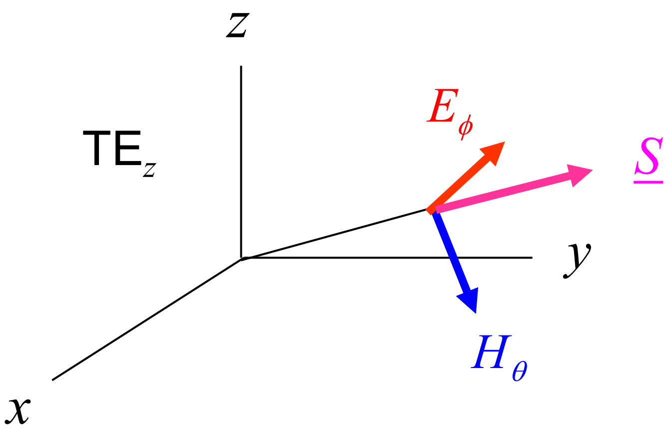
Example: vertical dipole



$$\frac{E_\theta}{H_\phi} = \eta_0$$

Depending on the type of antenna, either or both polarizations may be radiated (e.g., a vertical wire antenna radiates only E_θ polarization).

Example: horizontal loop antenna



$$\frac{E_\phi}{H_\theta} = -\eta_0$$

Antenna Radiation (cont.)

The power density in the far field is:

$$\underline{S}(r,\theta,\phi)=\underline{\hat{r}}\left(\left|E_\theta\right|^2+\left|E_\phi\right|^2\right)\left(\frac{1}{2\eta_0}\right)$$

or

$$\underline{S}(r,\theta,\phi)=\underline{\hat{r}}\left(\frac{\left|\underline{E}\right|^2}{2\eta_0}\right)$$

Antenna Radiation (cont.)

The far field always has the following form:

$$\underline{E}(r,\theta,\phi) = \left(\frac{e^{-jk_0r}}{r}\right)\underline{E}^{\mathrm{FF}}(\theta,\phi)$$

$\underline{E}^{\mathrm{FF}}(\theta,\phi) \equiv$ Normalized far-field electric field vector

In decibels (dB):

$$\mathrm{dB}(\theta,\phi) = 20\log_{10}\left(\frac{\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|}{\left|\underline{E}^{\mathrm{FF}}(\theta_m,\phi_m)\right|}\right)$$

$(\theta_m,\phi_m) =$ direction of maximum radiation

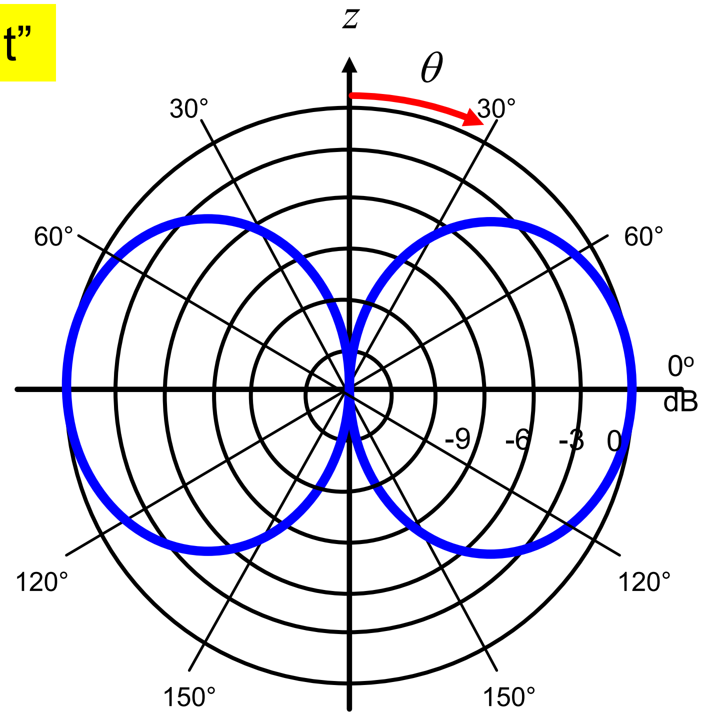
Antenna Radiation (cont.)

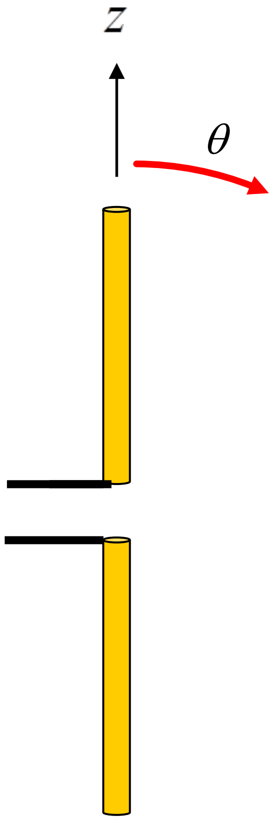
A normalized far-field pattern is usually shown vs. the angle θ (for a fixed angle $\phi = \phi_0$) in polar coordinates.

$$\mathrm{dB}\left(\theta,\phi_0\right) = 20\log_{10}\left(\frac{\left|\underline{E}^{\mathrm{FF}}\left(\theta,\phi_0\right)\right|}{\left|\underline{E}^{\mathrm{FF}}\left(\theta_m,\phi_0\right)\right|}\right)$$

The subscript "m" denotes the beam maximum.

An "elevation cut"

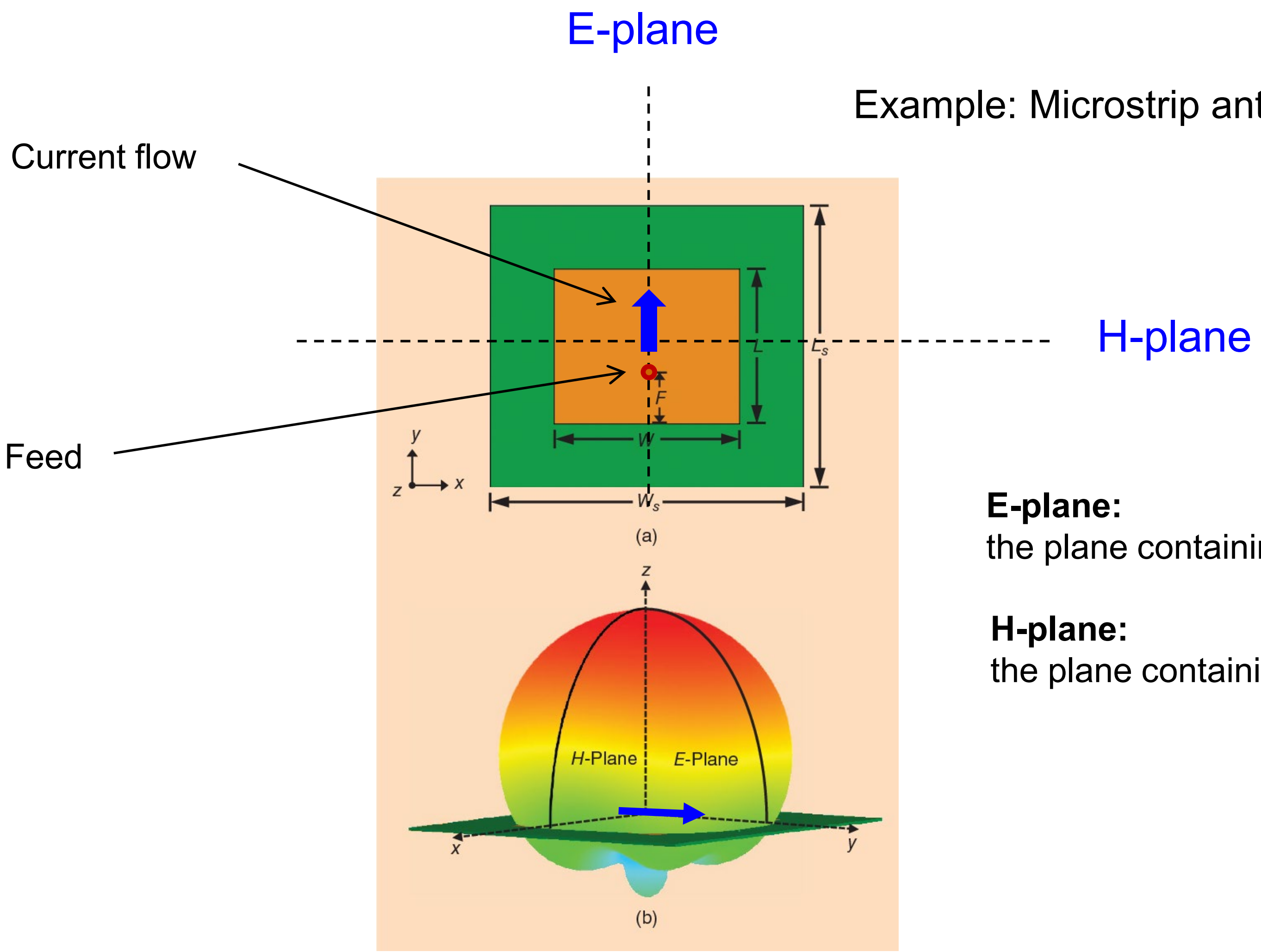




Antenna Radiation (cont.)

E-plane and H-plane

Example: Microstrip antenna


E-plane

Current flow

H-plane

Feed

E-plane:
the plane containing the $\underline{E}$ vector.

H-plane:
the plane containing the $\underline{H}$ vector.

Radiated Power

The Poynting vector in the far field is

$$\underline{S}(r,\theta,\phi)=\underline{\hat{r}}\left(\frac{\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|^{2}}{2\eta_{0}}\right)\left(\frac{1}{r^{2}}\right)\ \left[\mathrm{W/m^{2}}\right]$$

The total power radiated (in Watts) is then given by

$$P_{\mathrm{rad}}=\int_{0}^{2\pi}\int_{0}^{\pi}\left(\underline{S}\cdot\underline{\hat{r}}\right)r^{2}\sin\theta\,d\theta d\phi=\int_{0}^{2\pi}\int_{0}^{\pi}\left(\frac{\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|^{2}}{2\eta_{0}}\right)\sin\theta\,d\theta d\phi$$

Hence, we have

$$\boxed{P_{\mathrm{rad}}=\frac{1}{2\eta_{0}}\int_{0}^{2\pi}\int_{0}^{\pi}\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|^{2}\sin\theta\,d\theta d\phi}$$

Directivity

The directivity of the antenna in the directions (θ, ϕ) is defined as

$$D(\theta,\phi) \equiv \frac{S_r(\theta,\phi)}{P_{\text{rad}}/\left(4\pi r^2\right)} \qquad r \to \infty$$

The directivity (in a particular direction) is the ratio of the actual power density radiated in that direction to the power density that would be radiated in that direction if the antenna were an isotropic radiator (radiates equally in all directions).

In dB,

$$D_{\text{dB}}(\theta,\phi) = 10\log_{10} D(\theta,\phi)$$

Note: The directivity is sometimes referred to as the “directivity with respect to an isotropic radiator.”

Directivity (cont.)

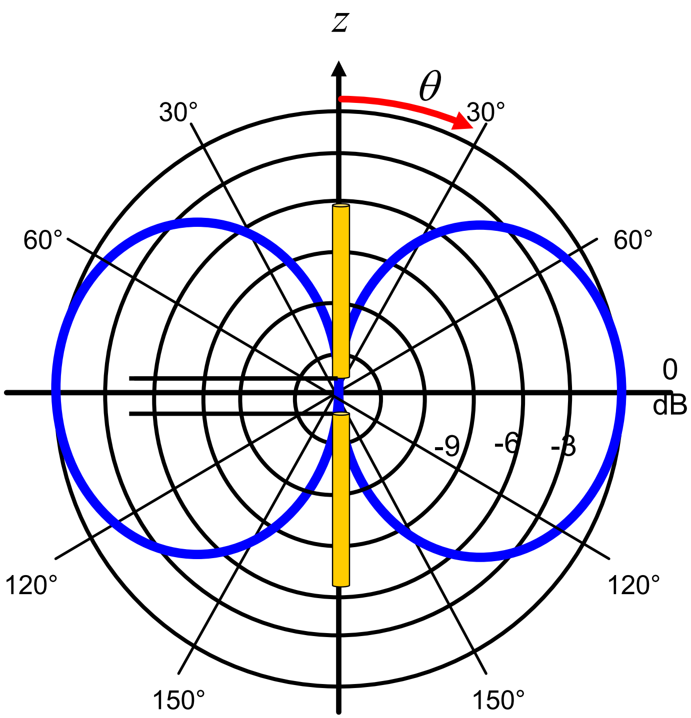
The directivity is then directly expressed in terms of the far field pattern:

$$D(\theta,\phi)=\frac{4\pi\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|^{2}}{\int\limits_{0}^{2\pi}\int\limits_{0}^{\pi}\left|\underline{E}^{\mathrm{FF}}(\theta,\phi)\right|^{2}\sin\theta\,d\theta d\phi}$$

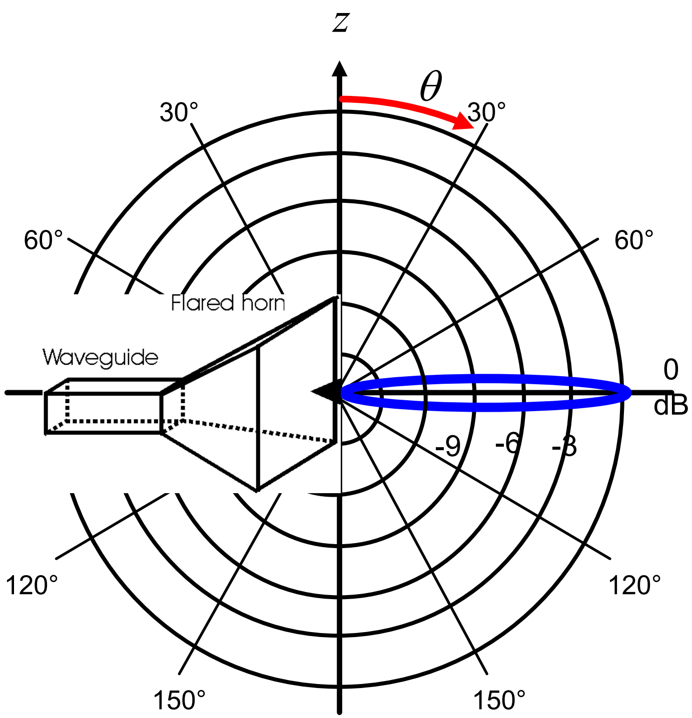
Usually, the directions are chosen to corresponds to the main beam direction:

$$D=D\left(\theta_{m},\phi_{m}\right)$$

Directivity (cont.)



Antenna with moderate directivity
(e.g., dipole)



Antenna with high directivity
(e.g., horn or dish)

Directivity (cont.)

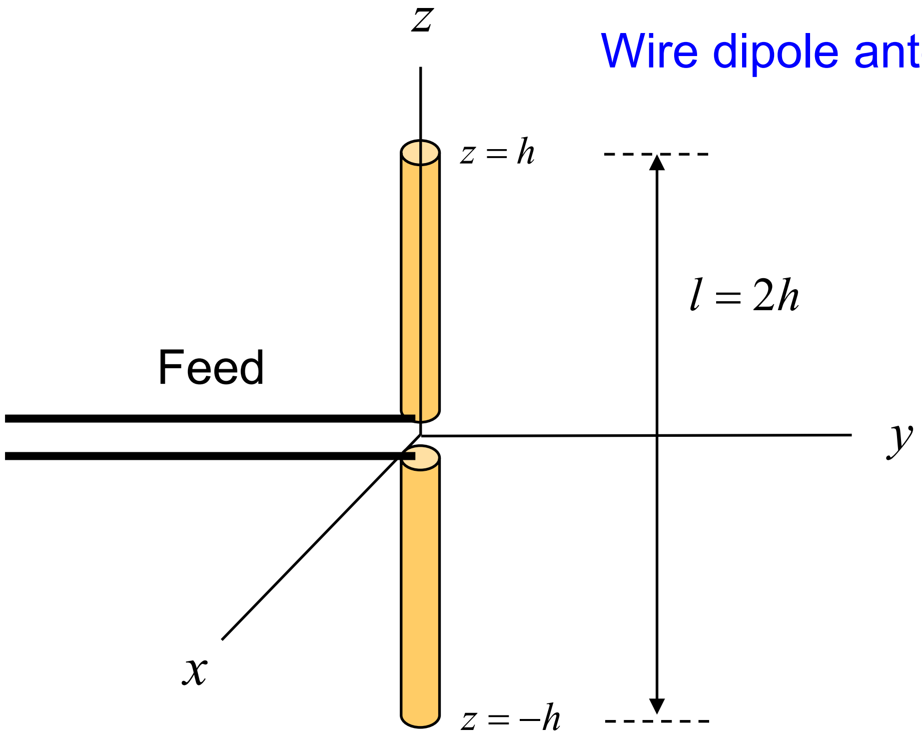
Two Common Cases: Dipole Antennas

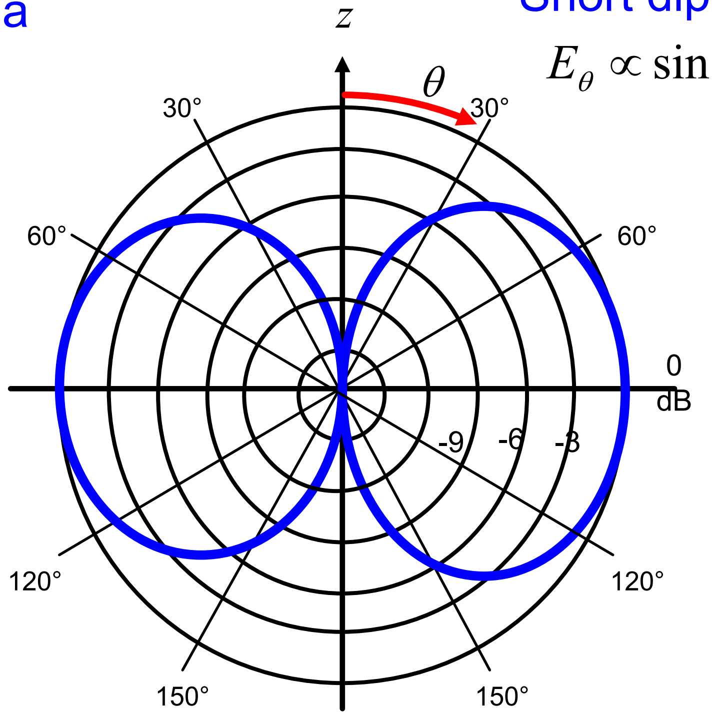
$\theta_m = \pi / 2$

$$D = D_{\max} = D\left(\pi / 2, \phi\right)$$

Short dipole wire antenna ($l << \lambda_0$): $\boldsymbol{D = 1.5}$

Resonant half-wavelength dipole wire antenna ($l = \lambda_0 / 2$): $\boldsymbol{D = 1.643}$


Wire dipole antenna

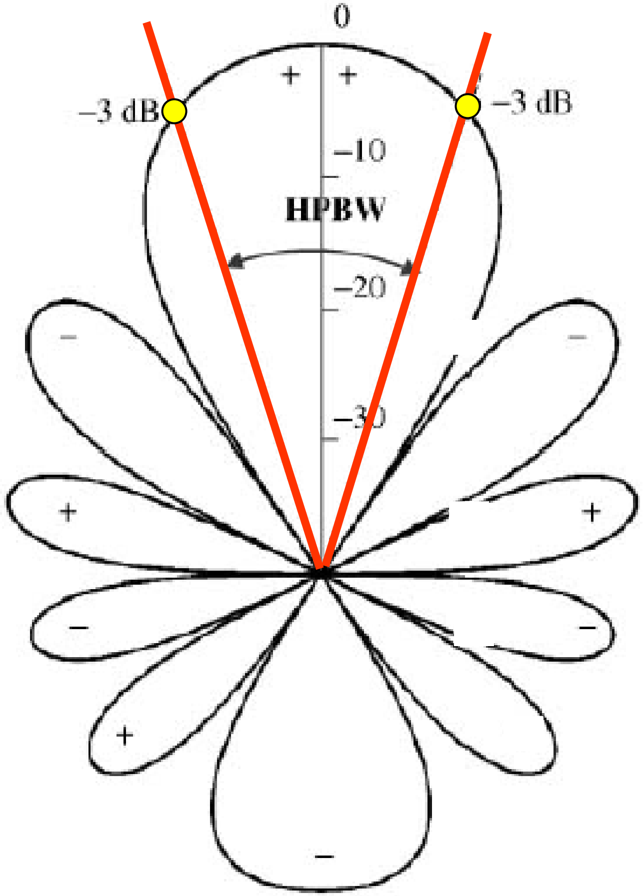

Short dipole

$E_\theta \propto \sin\theta$

Beamwidth

The beamwidth measures how narrow the beam is
(the narrower the beamwidth, the higher the directivity).

HPBW = half-power beamwidth



At the "half-power" points:

The power density is down by a factor of 1/2.

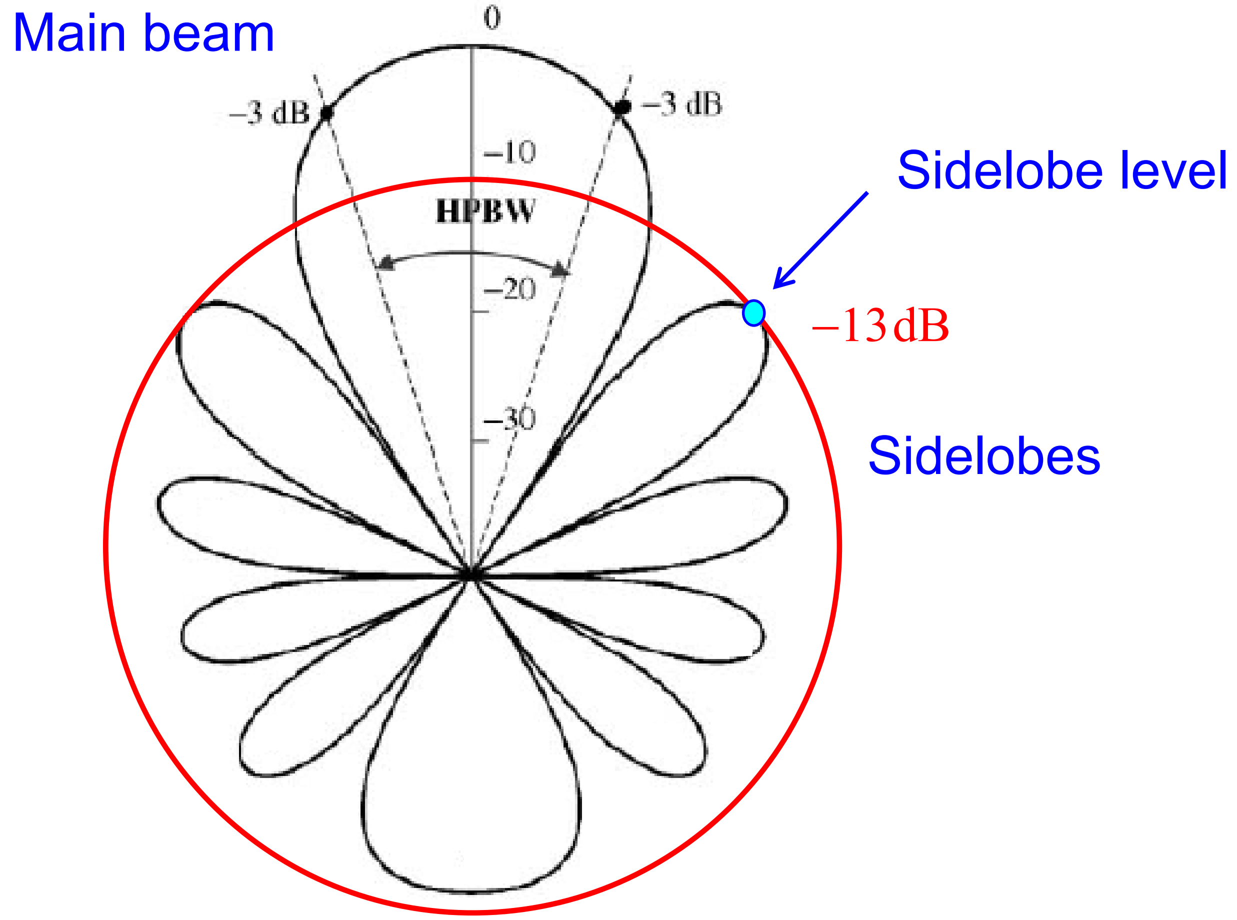
The field is down by a factor of $1/\sqrt{2} = 0.707$.

In dB, we are down by 3 dB.

Sidelobe Level

The sidelobe level measures how large the sidelobes are.

In this example the sidelobe level is about -13 dB.



Gain and Efficiency

The radiation efficiency of an antenna is defined as

$$e_r \equiv \frac{P_{\text{rad}}}{P_{\text{in}}}$$

P_{rad} = power radiated by the antenna

P_{in} = power input to the antenna

The gain of an antenna in the directions (θ, ϕ) is defined as

$$G(\theta,\phi) \equiv e_r \, D(\theta,\phi)$$

In dB, we have

$$G_{\text{dB}}(\theta,\phi) = 10\log_{10} G(\theta,\phi)$$

Gain and Efficiency (cont.)

The gain tells us how strong the radiated power density is in a certain direction, for a given amount of input power.

Recall that

$$D(\theta,\phi) \equiv \frac{S_r(\theta,\phi)}{P_{\text{rad}} / \left(4\pi r^2\right)} \qquad r \to \infty$$

Therefore, in the far field:

$$S_r(\theta,\phi) = \left[P_{\text{rad}} / \left(4\pi r^2\right)\right] D(\theta,\phi)$$

$$\Downarrow$$

$$S_r(\theta,\phi) = \left[e_r P_{\text{in}} / \left(4\pi r^2\right)\right] D(\theta,\phi)$$

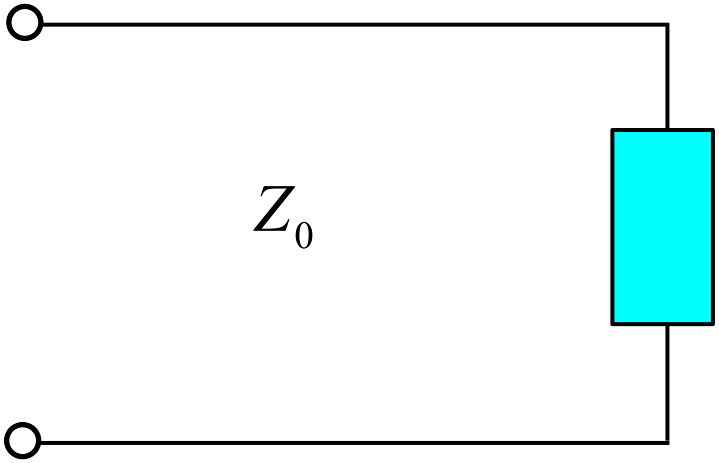
Recall: $G(\theta,\phi) \equiv e_r \, D(\theta,\phi)$

$$\Downarrow$$

$$S_r(\theta,\phi) = \left[P_{\text{in}} / \left(4\pi r^2\right)\right] G(\theta,\phi)$$

Input Impedance

The antenna acts like a load impedance during transmit.



$$Z_{\text{in}} = R_{\text{in}} + jX_{\text{in}}$$

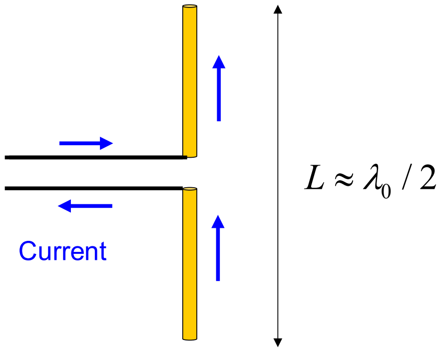
At resonance, the input reactance X_{in} is zero (the desired situation).

Note: We usually want a match between the input impedance and the characteristic impedance Z_0 of the feeding transmission line, to avoid reflection.

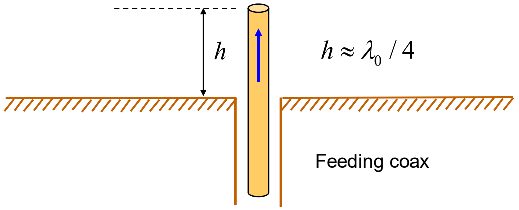
Input Impedance (cont.)

At resonance:

Dipole: $Z_{\text{in}} \approx 73\ [\Omega]$

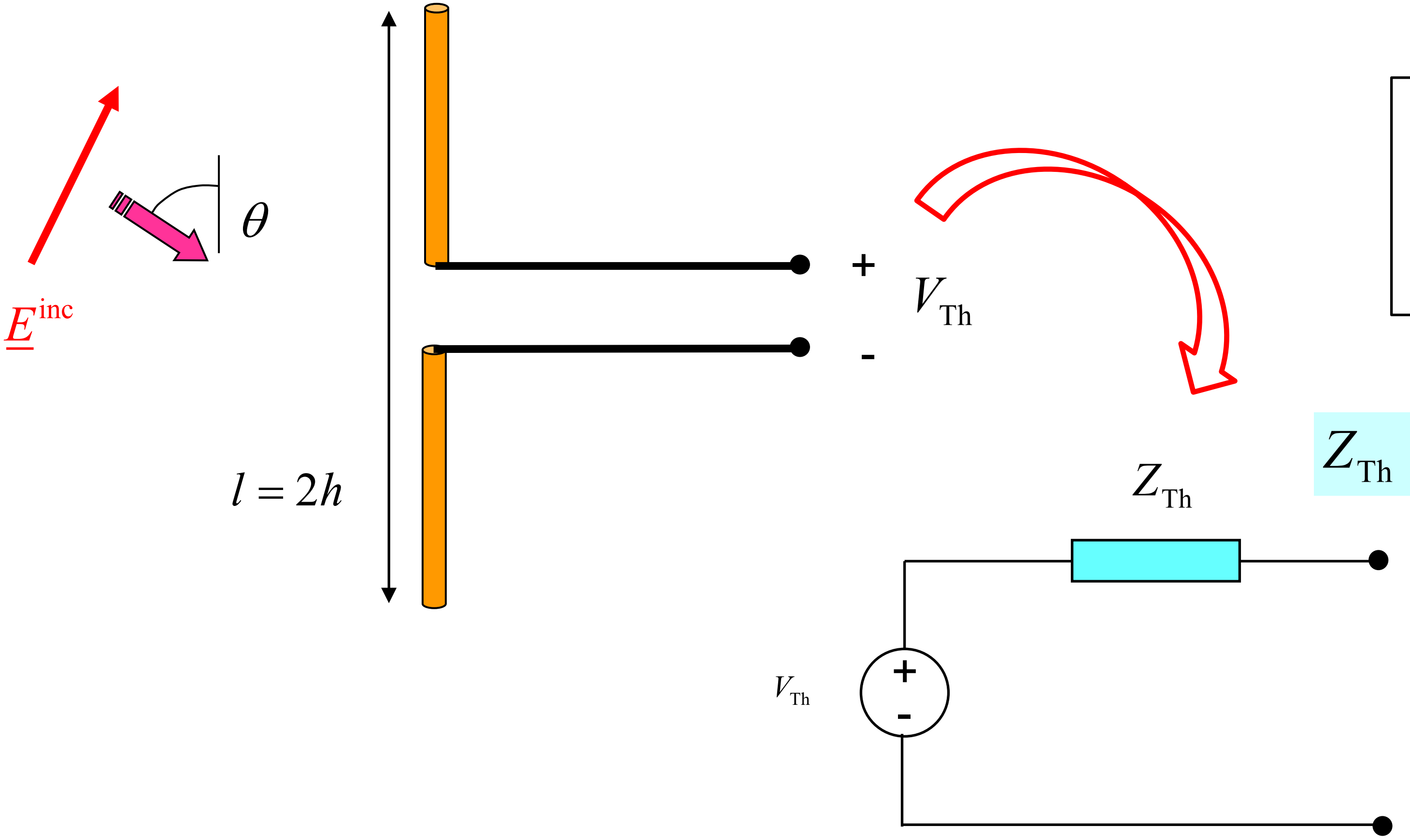


Monopole: $Z_{\text{in}} \approx 36.5\ [\Omega]$



Receive Antenna

The Thévenin equivalent circuit of an antenna being used as a receive antenna is shown below.



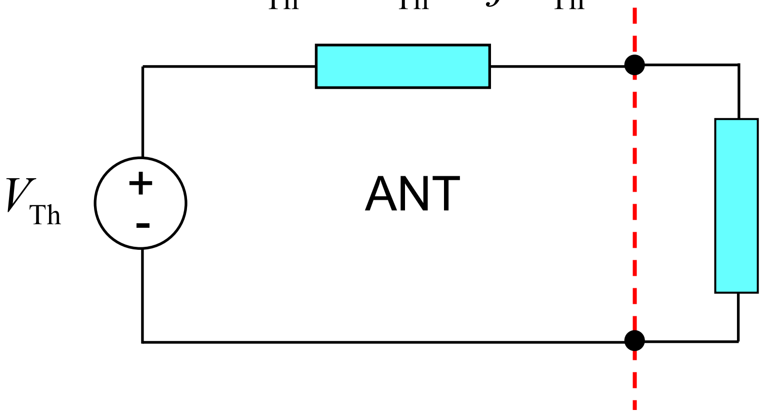
The Thevenin impedance is the same as the input impedance of the antenna.

$$Z_{\text{Th}} = Z_{\text{in}}$$

Receive Antenna (cont.)

The power received by an optimum conjugate-matched load:

$$Z_{\text{Th}} = R_{\text{Th}} + jX_{\text{Th}}$$



Load

$$Z_L = Z_{\text{Th}}^* = R_{\text{Th}} - jX_{\text{Th}}$$

$P_{\text{rec}} = P_L =$ power absorbed by load

For a <u>resonant</u> dipole wire antenna:

$$X_{\text{Th}} = X_{\text{in}} = 0$$

$$R_{\text{Th}} = R_{\text{in}} = 73\ [\Omega]$$

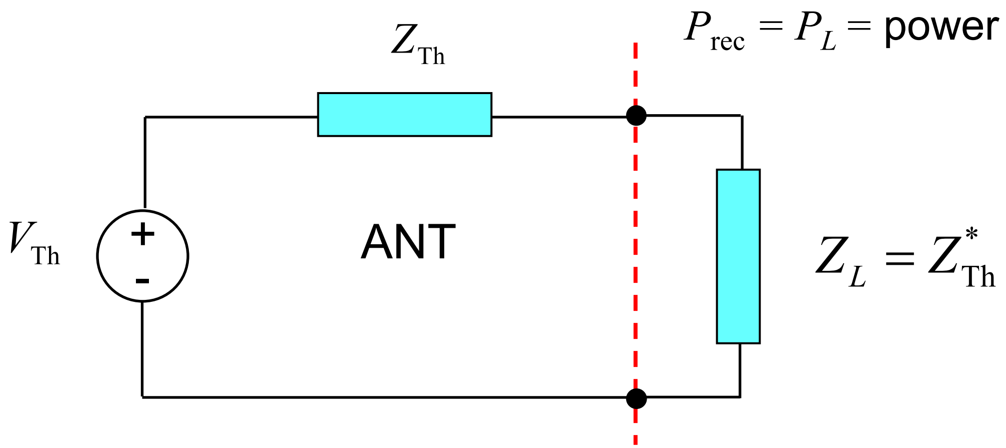
⇒

$$R_{\text{Th}} = 73\ [\Omega]$$

Receive Antenna (cont.)

We can find the power received using an effective area.

Receive circuit: Assume an optimum conjugate-matched load:



$P_{\mathrm{rec}} = P_L =$ power absorbed by load

$$\boxed{P_{\mathrm{rec}} = A_{\mathrm{eff}} P_d^{\mathrm{inc}}}$$

$A_{\mathrm{eff}} =$ effective area of antenna

$P_d^{\mathrm{inc}} =$ power density of incident wave $\left[\mathrm{W/m^2}\right]$

Receive Antenna (cont.)

We have the following general formula*:

$$A_{\text{eff}} = G\left(\frac{\lambda_0^2}{4\pi}\right)$$

$G = G(\theta,\phi) =$ gain of antenna in direction (θ,ϕ)

(Usually, we assume that (θ,ϕ) is in the main beam direction.)

*A derivation is given in the following book:
C. A. Balanis, *Antenna Engineering,* 3rd Ed., 2016, Wiley.

Receive Antenna (cont.)

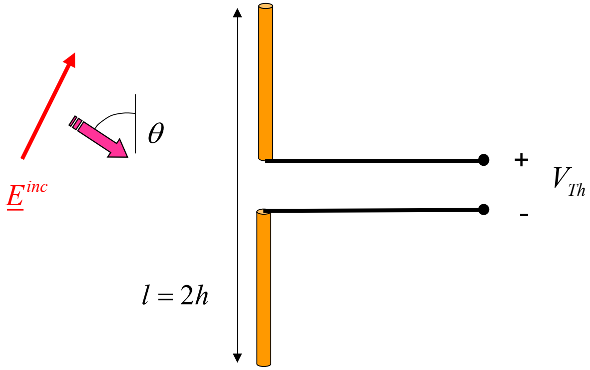
Effective area of a lossless resonant half-wave dipole antenna:

Assuming normal incidence ($\theta = 90^{\circ}$):

$$A_{\text{eff}} = G\left(\frac{\lambda_0^2}{4\pi}\right)$$

$$= 1.643\left(\frac{\lambda_0^2}{4\pi}\right) \qquad \left(D = D_{\max} = 1.643\right)$$

$$= 1.643\left(\frac{(2l)^2}{4\pi}\right) \qquad \left(l = \lambda_0 / 2\right)$$



Assume lossless antenna:
$e_r = 100\%$
$(G = D)$

Hence:

$$A_{\text{eff}} = 0.523\ l^2$$

Note: The dipole will receive more power at a lower frequency (larger l), assuming the same incident power.

Example with Wire Antennas

Example

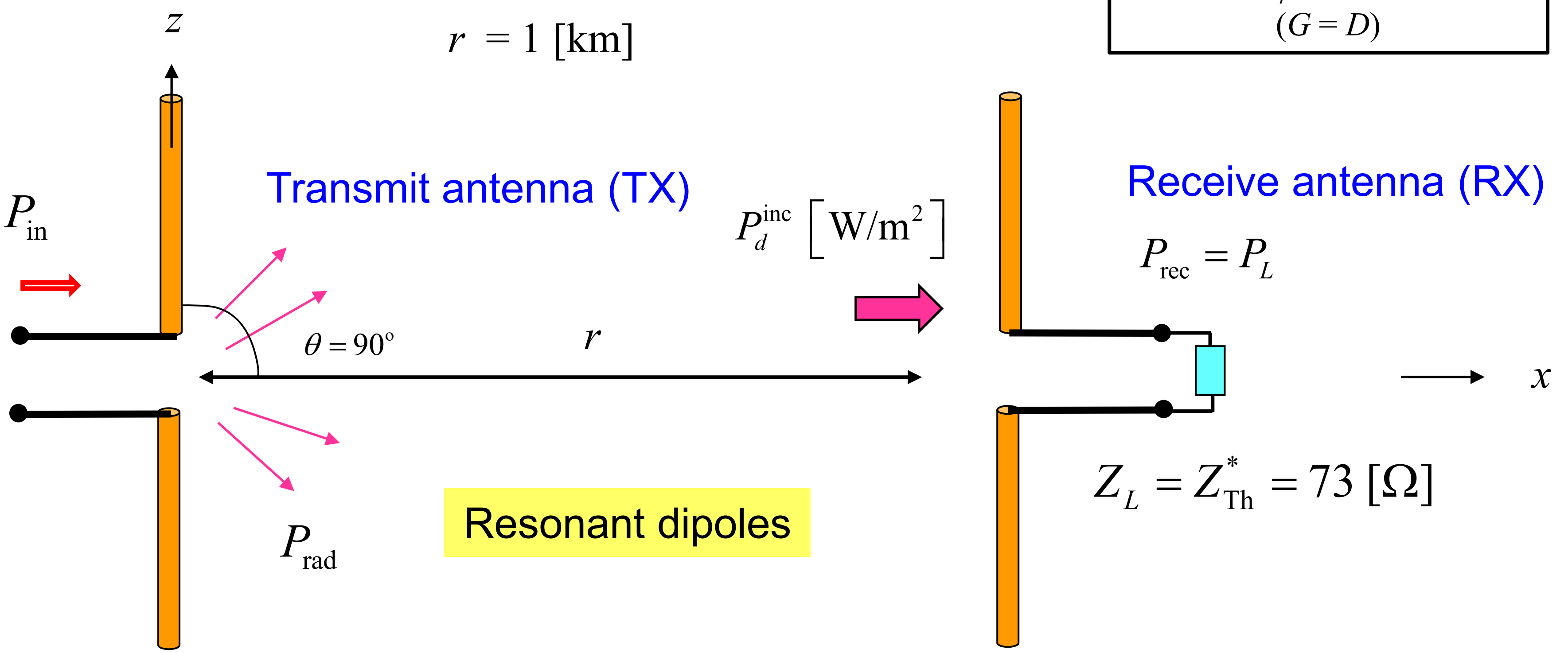
Find the received power P_{rec} in the example below, assuming that the receiver is connected to an optimum conjugate-matched load.

$$f = 1\ [\text{GHz}]\ \ (\lambda_0 = 0.29979\ [\text{m}])$$

$$P_{\text{in}} = 10\ [\text{W}]$$

$$r = 1\ [\text{km}]$$

Assume lossless antennas:
$e_r = 100\%$
$(G = D)$



Resonant dipoles

Example with Wire Antennas (cont.)

$$P_{\text{rec}} = A_{\text{eff}} P_d^{\text{inc}}$$

Gain of RX

$$A_{\text{eff}} = 1.643\left(\frac{\lambda_0^2}{4\pi}\right)$$

Gain of TX

$$P_d^{\text{inc}} = \frac{P_{\text{in}}}{4\pi r^2}(1.643)$$

Hence:

$$P_{\text{rec}} = \left[1.643\left(\frac{\lambda_0^2}{4\pi}\right)\right]\left[\frac{P_{\text{in}}}{4\pi r^2}(1.643)\right]$$

The result is:

$$P_{\text{rec}} = 1.54\times 10^{-8}\ [\text{W}]$$

Receive Antenna (cont.)

Effective area of dish (reflector) antenna

In the maximum gain (main beam) direction:

$$A_{\text{eff}} = A_{\text{phy}} e_{\text{ap}}$$

Now it is the effective area that we know, and from this we can calculate the gain.

A_{phy} = physical area of dish

e_{ap} = "aperture efficiency"

$$A_{\text{eff}} = G\left(\frac{\lambda_0^2}{4\pi}\right)$$

The aperture efficiency is usually less than 1 (less than 100%).

Gain of Dish Antenna

Dish antenna:

Obtaining a higher gain means having a larger dish.

$$G = A_{\mathrm{eff}}\left(\frac{4\pi}{\lambda_0^2}\right)$$

$$\Downarrow \qquad A_{\mathrm{eff}} = A_{\mathrm{phy}}\,e_{\mathrm{ap}}$$

$$\boxed{G = 4\pi\left(\frac{A_{\mathrm{phy}}}{\lambda_0^2}\right)e_{\mathrm{ap}}}$$

Example with Dish Antenna

Example

A microstrip antenna on a CubeSat with a gain of 8 (9.03 dB) transmits with an input power of 1 [W] at 10.0 GHz from a distance of 50,000,000 [km] (near Mars).

How much power will be received by the NASA Deep Space Network dish at Goldstone, CA, which has a diameter of 70 [m]? Assume an aperture efficiency of 0.75 (75%).

Express answer in Watts and in dBm (dB relative to a milliwatt).

Note : $P_{\text{rec}}^{\text{dBm}} \equiv 10\log_{10}\left(\dfrac{P_{\text{rec}}}{0.001\ [\text{W}]}\right)$

Example with Dish Antenna (cont.)

Example (cont.)

$$P_{\text{rec}} = P_d^{\text{inc}} A_{\text{eff}} = \underset{\big\uparrow}{P_d^{\text{inc}}} A_{\text{phy}} e_{\text{ap}}$$

$$P_d^{\text{inc}} = \left(\frac{P_{\text{in}}}{4\pi r^2} \right) G_{\text{trans}}$$

$$P_{\text{rec}} = 1.014^{-19} \, [\text{W}]$$

$$P_{\text{rec}}^{\text{dBm}} = -151.3$$

Parameters:

$$r = 5.0 \times 10^{10} \; [\text{m}]$$

$$A_{\text{phy}} = \pi (70/2)^2 \; [\text{m}^2]$$

$$e_{\text{ap}} = 0.75$$

$$P_{\text{in}} = 1 \, [\text{W}]$$

$$G_{\text{trans}} = 8$$