EMPossible

Electromagnetics:

Microwave Engineering

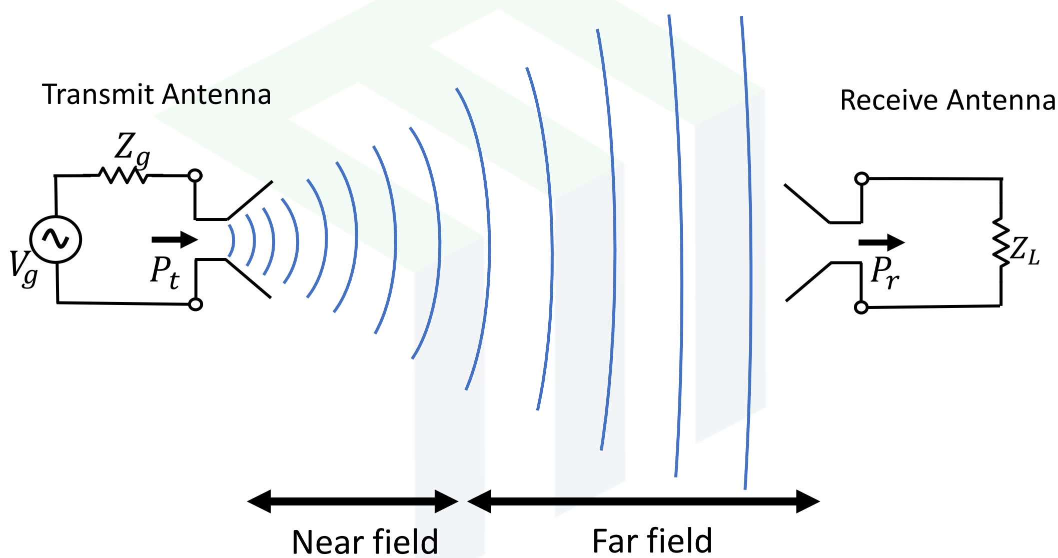
System Aspects of Antennas

Lecture Outline

- Introduction
- Fields and Power Radiated by an Antenna
- Antenna Pattern Characteristics
- Antenna Gain and Efficiency
- Aperture Efficiency and Effective Area

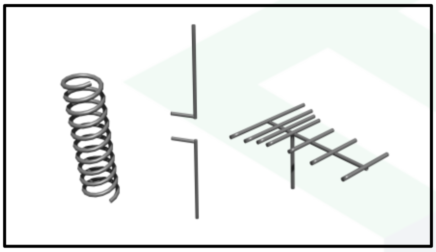
Field Detachment from Antennas

Basic Antenna Communication System

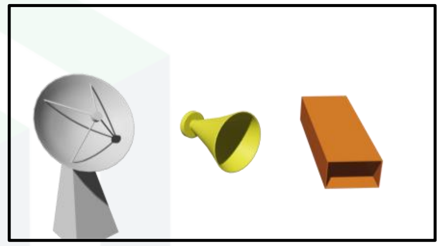


Types of Antennas

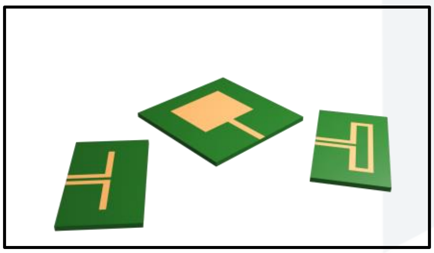
Wire Antennas



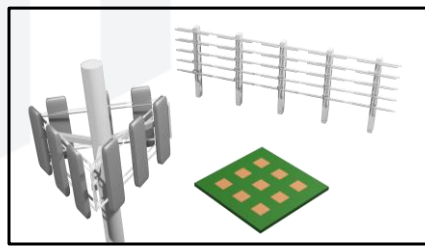
Aperture Antennas



Printed Antennas



Array Antennas



EMPossible

Fields and Power Radiated by an Antenna

At large distances (far field), the radiated electric field of an antenna is

$$\vec{E}(r,\theta,\phi) = \left[\underbrace{\hat{\theta}F_\theta(\theta,\phi)} + \underbrace{\hat{\phi}F_\phi(\theta,\phi)}\right]\frac{e^{-jk_0 r}}{r} \quad \text{V/m}$$

Pattern Functions

$$k_0 = \frac{2\pi}{\lambda}$$

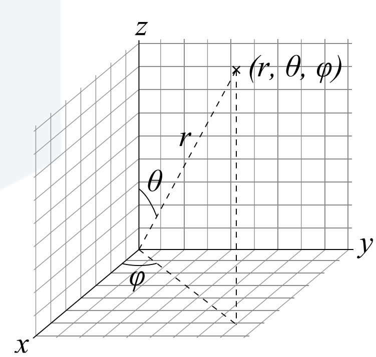
$$\lambda = \frac{c_0}{f}$$

$$\eta_0 = 377\ \Omega$$

The magnetic fields associated with the electric field are

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

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



EMPossible

Fields and Power Radiated by an Antenna

The Poynting vector is given by

$$\vec{S} = \vec{E} \times \vec{H}^*$$

And the average-time Poynting vector is given by

$$\vec{S}_{avg} = \frac{1}{2}\text{Re}\{\vec{S}\} = \frac{1}{2}\left[\vec{E} \times \vec{H}^*\right] \ \text{W/m}$$

The far-field is the distance where a spherical wavefront approximates a planar phase front of a plane wave. The distance can be approximated as

$$R_{ff} = \frac{2D^2}{\lambda}$$

$$D - max.\,antenna\ dimension$$

For electrically small antennas, $R_{ff} = 2\lambda$

EMPossible

Example: Far-Field Distance of an Antenna

A parabolic reflector antenna used for reception with the direct-broadcast system (DBS) is 18 in. in diameter and operates at 12.4 GHz. Find the far-field distance for this antenna.

Solution:

At 12.4 GHz, the wavelength is $\lambda = \frac{c_0}{f} = 2.42\ \text{cm} = 0.0242\ \text{m}$

The maximum dimension of the antenna is 18 inches, or 0.457 m

$$R_{ff} = \frac{2D^2}{\lambda} = \frac{2(0.457)^2}{0.0242} = 17.3\ \text{m}$$

The far-field distance is 17.3 m and the DBS satellite to Earth is 36,000 km, so it is safe to assume that the receive antenna is in the far-field of the parabolic antenna.

EMPossible

Radiation Intensity

The radiation intensity is defined as

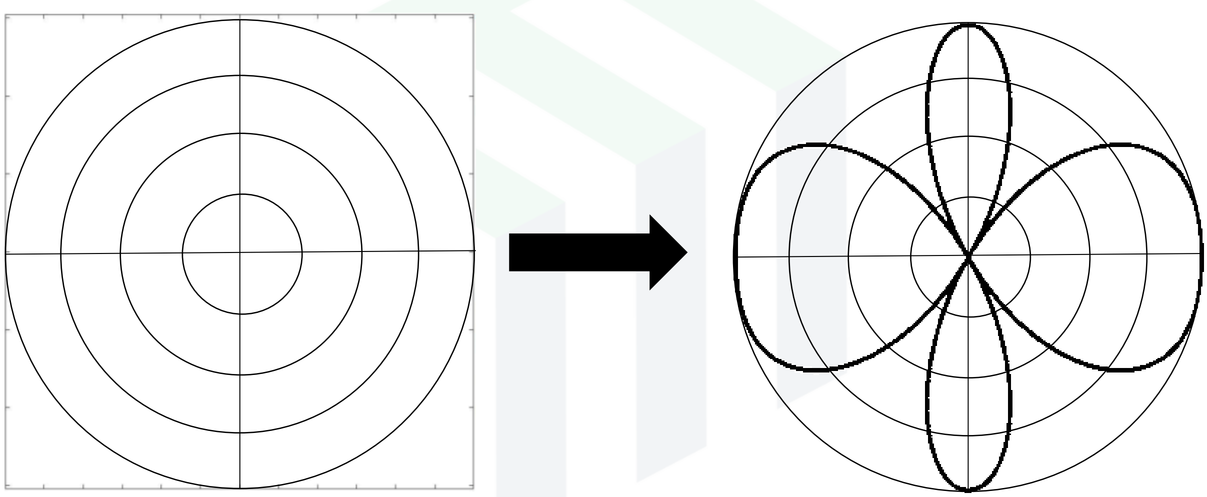
$$U(\theta,\phi) = r^2\left|\vec{S}_{avg}\right| = \frac{r^2}{2}\left\{E_\theta\hat{\theta}\times H_\phi^*\hat{\phi} + E_\phi\hat{\phi}\times H_\theta^*\hat{\theta}\right\}$$
$$= \frac{r^2}{2\eta_0}\left[\left|E_\theta\right|^2 + \left|E_\phi\right|^2\right] = \frac{1}{2\eta_0}\left[\left|F_\theta\right|^2 + \left|F_\phi\right|^2\right] \quad \text{W}$$

The total power radiated by an antenna can be obtained by integrating the Poynting vector over the surface of a sphere of radius r that encloses the antenna.

$$P_{rad} = \iint_{\phi=0\ \theta=0}^{2\pi\ \pi} \vec{S}_{avg}\bullet\hat{r}r^2\sin\theta\, d\theta d\phi = \iint_{\phi=0\ \theta=0}^{2\pi\ \pi} U(\theta,\phi)\sin\theta\, d\theta d\phi$$

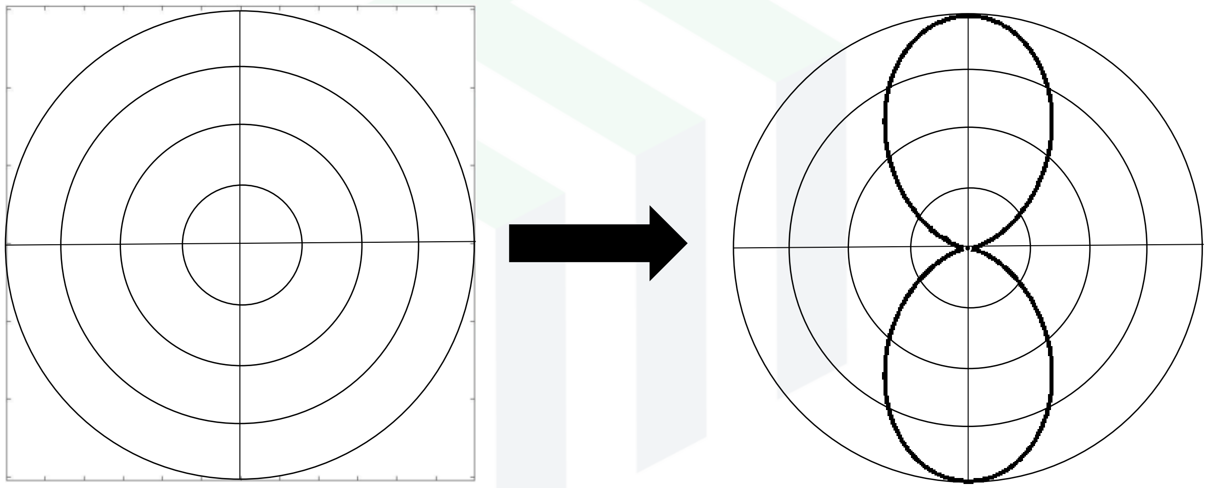
Antenna Pattern Characteristics (Radiation Pattern)

Two-element array with spacing $d=\lambda$ between elements



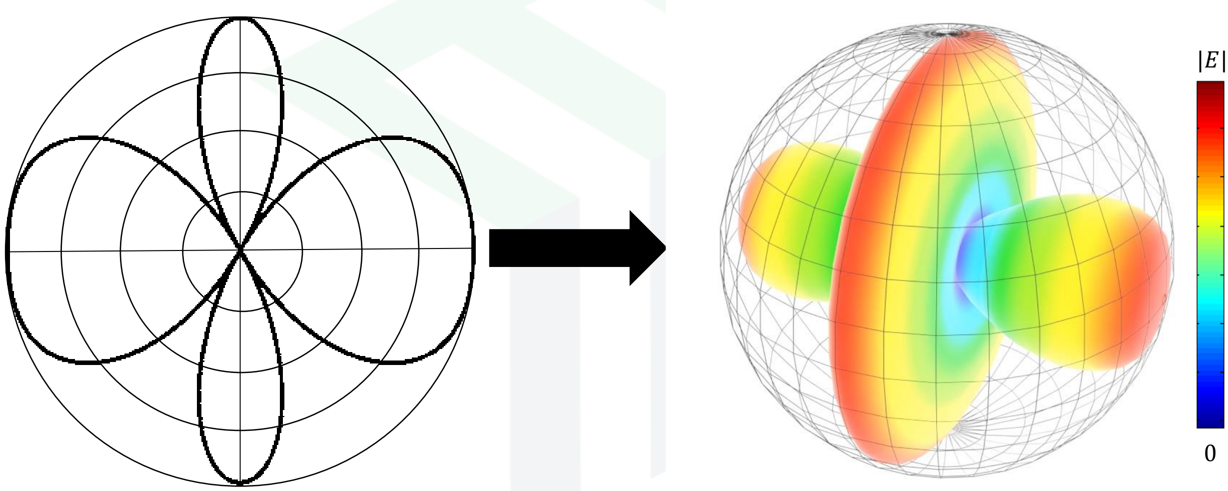
Antenna Pattern Characteristics (Radiation Pattern)

Two-element array with spacing $d = \lambda/2$ between elements



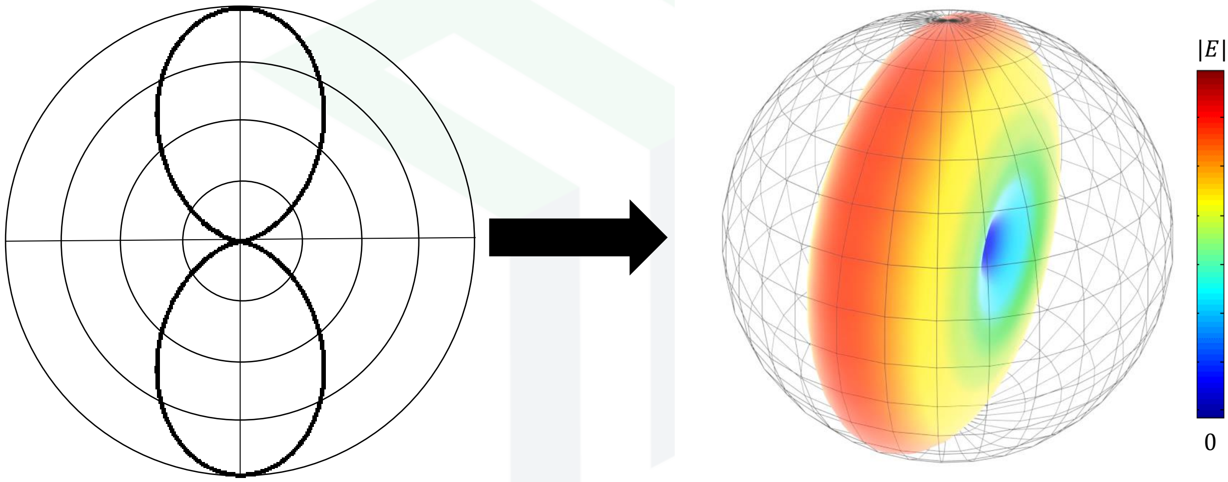
Antenna Pattern Characteristics (Radiation Pattern)

Two-element array with spacing $d = \lambda$ between elements



Antenna Pattern Characteristics (Radiation Pattern)

Two-element array with spacing $d = \lambda/2$ between elements

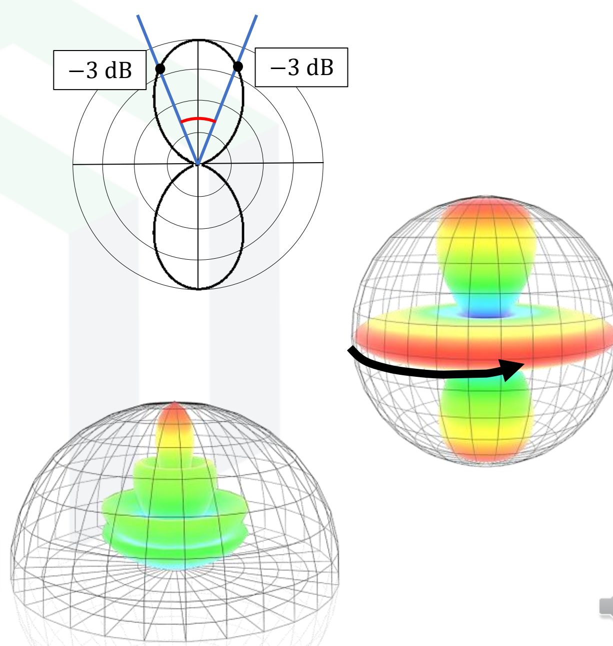


EMPossible 13

Antenna Pattern Characteristics

A fundamental property of an antenna is its ability to focus power in a given direction while excluding others. Some measures of the focusing properties of antennas are:

- 3 dB beamwidth: Angular width of the main beam that drops 3 dB from maximum value
- Omnidirectional antenna: Antennas with constant pattern in its azimuthal plane
- Pencil Beam Antennas: Antennas with a main narrow beam



EMPossible 14

Antenna Directivity

Directivity: The ratio of the maximum radiation intensity in the main beam to the average radiation intensity over all space.

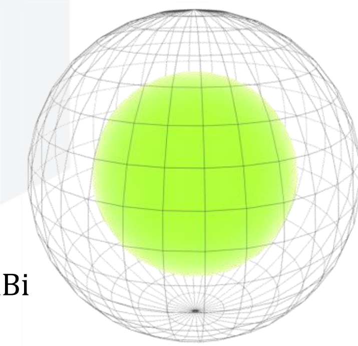
$$D = \frac{U_{max}}{U_{avg}} = \frac{4\pi U_{max}}{P_{rad}} = \frac{4\pi U_{max}}{\iint_{\phi=0\ \theta=0}^{2\pi\ \pi} U(\theta,\phi)\sin\theta\, d\theta d\phi}$$

Directivity is a dimensionless ratio expressed as

$$D(\mathrm{dB}) = 10\log(\mathrm{D})$$

An isotropic antenna radiates equally in all directions ($U(\theta,\phi) = 1$), therefore $D = 1 = 0\ \mathrm{dB}$

Directivity in relation to an isotropic antenna is referred as dBi



EMPossible

15

Antenna Directivity

Directivities from common antennas are:

Wire dipole ($L = \lambda/2$): $2.15\ \mathrm{dB}$
Microstrip Patch: $7.0\ \mathrm{dB}$
Waveguide Horn: $23\ \mathrm{dB}$
Parabolic Reflector: $35\ \mathrm{dB}$

The $3\ \mathrm{dB}$ beamwidth and directivity are both measures of the focusing ability of an antenna:

Pattern with narrow main beam → Higher directivity
Pattern with broad main beam → Lower directivity

An approximation for directivity for pencil (narrow) beam antennas is

$$D = \frac{32{,}400}{\theta_1 \theta_2}$$

θ_1, θ_2- Beamwidths along 2 orthogonal planes in degrees

EMPossible

16

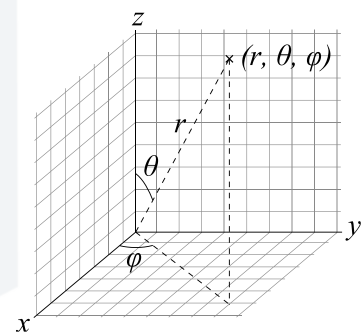
Example: Pattern Characteristics of a Dipole Antenna

The far-zone electric field radiated by an electrically small $(L < \lambda/10)$ wire dipole antenna oriented on the z −axis is given by

$$E_\theta(r,\theta,\phi) = V_0 \sin\theta \frac{e^{-jk_0 r}}{r} \text{ V/m}$$

$$E_\phi(r,\theta,\phi) = 0$$

Find the beam position of the antenna, its 3 dB beamwidth, and directivity.

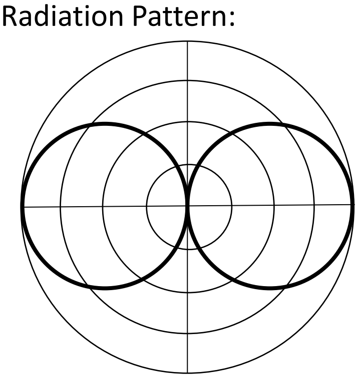


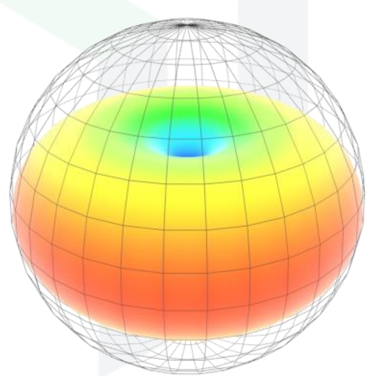
Example: Pattern Characteristics of a Dipole Antenna

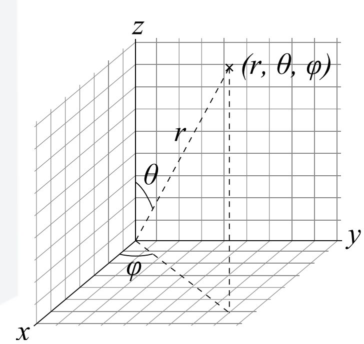
Solution:

$$U(\theta,\phi) = \frac{r^2}{2\eta_0}\left[\left|E_\phi\right|^2\right] = \frac{r^2 V_0^2}{2\eta_0 r^2}\sin^2\theta = \frac{V_0^2}{2\eta_0}\sin^2\theta$$

Radiation Pattern:







Example: Pattern Characteristics of a Dipole Antenna

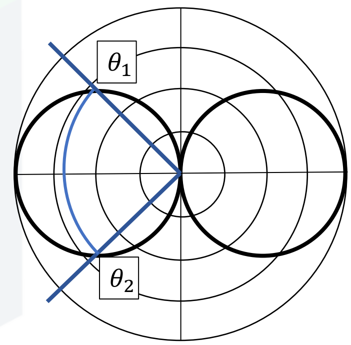
Solution:

The angles where the radiation intensity drops by 3 dB are given by the solutions to

$$\sin^2\theta = 0.5$$

$$\theta_1 = \frac{\pi}{4} = 135^\circ \qquad \theta_2 = \frac{3\pi}{4} = 45^\circ$$

$$\theta_{(3\text{ dB})} = 135^\circ - 45^\circ = 90^\circ$$



EMPossible

19

Example: Pattern Characteristics of a Dipole Antenna

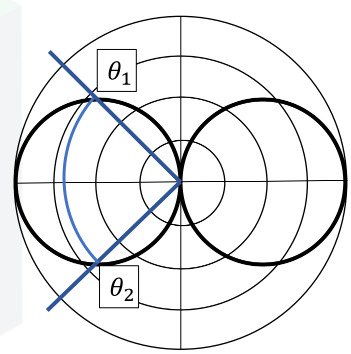
Solution:

The directivity is calculated by

$$D = \frac{4\pi U_{max}}{\iint_{\phi=0\ \theta=0}^{2\pi\ 2\pi} U(\theta,\phi)\sin\theta\, d\theta d\phi}$$

$$D = \frac{4\pi U_{max}}{2\pi \frac{V_0^2}{2\eta_0}\int_{\theta=0}^{\pi}\sin^3\theta\, d\theta} = \frac{4\pi \frac{V_0^2}{2\eta_0}}{2\pi \frac{V_0^2}{2\eta_0}\left(\frac{4}{3}\right)} = \frac{3}{2} = 1.5$$

$$\boxed{D = 1.5 = 10\log(1.5) = 1.76\text{ dB}}$$



EMPossible

20

Antenna Gain and Efficiency

Resistive losses exist in all practical antennas. Radiation efficiency takes losses into account by taking the ratio of the desired output power to the supplied input power.

$$\eta_{rad} = \frac{P_{rad}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}}$$

$P_{rad} \rightarrow$ Power radiated by the antenna
$P_{in} \rightarrow$ Power supplied to the input of the antenna
$P_{loss} \rightarrow$ Power lost in the antenna

The antenna gain is the product of directivity and efficiency:

$$G = \eta_{rad} D$$

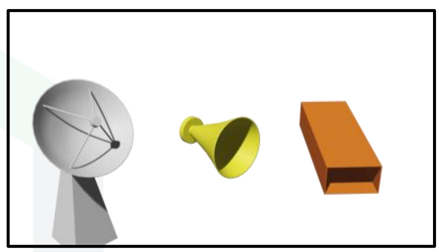
Directivity is usually expressed in dB $\quad G(\text{dB}) = 10\log(\text{G})$

EMPossible

21

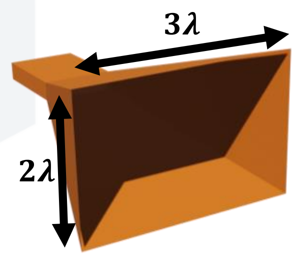
Aperture Efficiency and Effective Area

Many antennas are classified as aperture antennas, which have a well defined area from which radiation occurs. In these antennas, the maximum directivity can be obtained from an electrically large aperture of area A given as



$$D_{max} = \frac{4\pi A}{\lambda^2}$$

For example, for a rectangular horn antenna (right), the maximum directivity would be



$$D_{max} = \frac{4\pi(3\lambda)(2\lambda)}{\lambda^2} = 24\pi = 18.77 \text{ dB}$$

EMPossible

22

Aperture Efficiency and Effective Area

Reciprocity Theorem: The receive and transmit properties of antennas are identical. Terms like directivity, radiation pattern, efficiency, and gain apply to both transmit and receive antennas.

For a receiving antenna, it is of interest to determine the received power from an incident plane wave. This is determined by

$$P_r = A_e S_{avg}$$

$A_e \rightarrow$ Effective aperture area

$$A_e = \frac{D\lambda^2}{4\pi}$$

To account for losses, D can be replaced with G