Antennas: From Ham Radio to Modern Communication Systems

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Agenda

1. **Antenna Theory**
   - **Radiation Mechanism**
   - **Antenna Parameters**

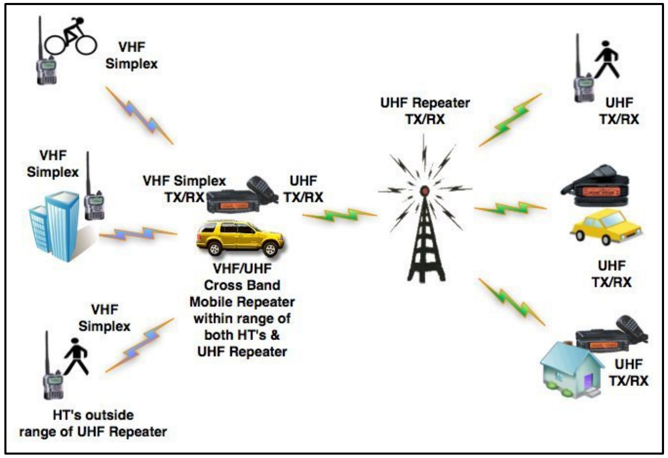
2. **Antenna Applications**
   - **Ham Radio**
   - **Satellite Communication**
   - **5G Cellular Communication**
   - **Antenna Array**

Antenna Theory

Antenna Applications

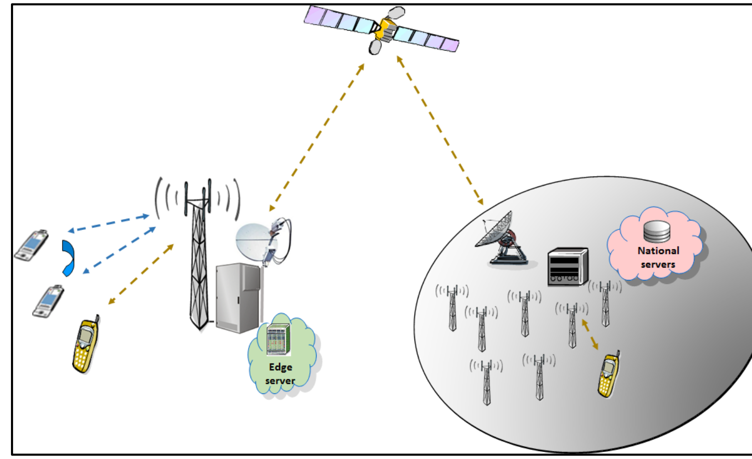
Wireless Communication

Ham Radio



https://myoffroadradio.com/what-is-a-ham-radio-repeater/

Cellular and Satellite Communication



https://www.cell-sat.com/en/solutions/local_switching_local_processing.html

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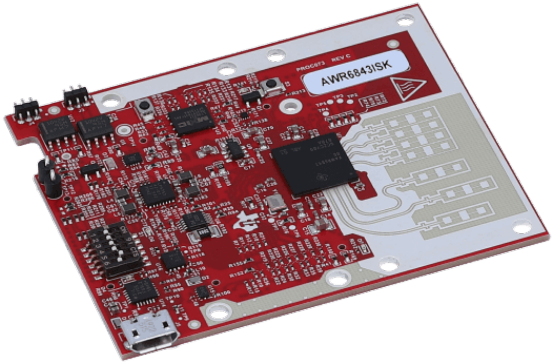
Radar & Sensor

Airport Scanning Radar Antenna

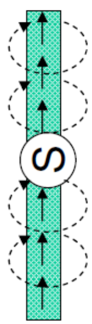
TI Automotive Radar Sensor



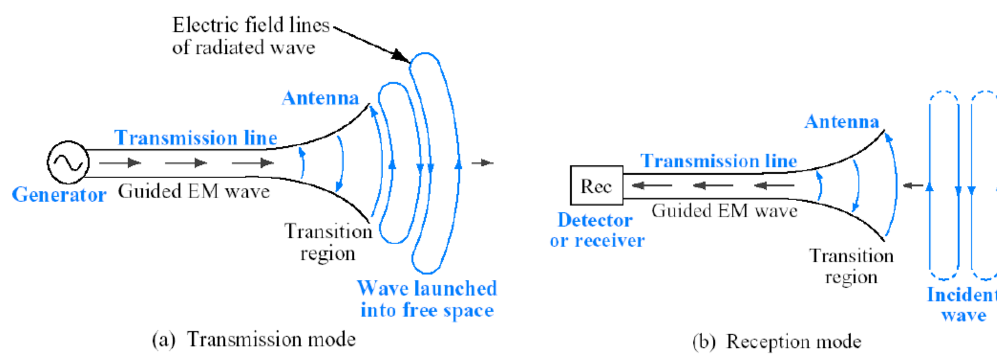
An antenna is an essential element for all wireless communication systems and most of radars and sensors.

How Antennas Radiate*

- Physics behind: Radiation is created by accelerated charges
- Accelerating charges -> changing electric and magnetic fields -> propagating electromagnetic waves.
- I = q·v (current = charge x velocity)
- dI/dt = q · dv/dt (time varying current = accelerated charge)
- Time-varying current source (accelerated charges) exposed under an open space creates radiation.



Electric current induces radiation



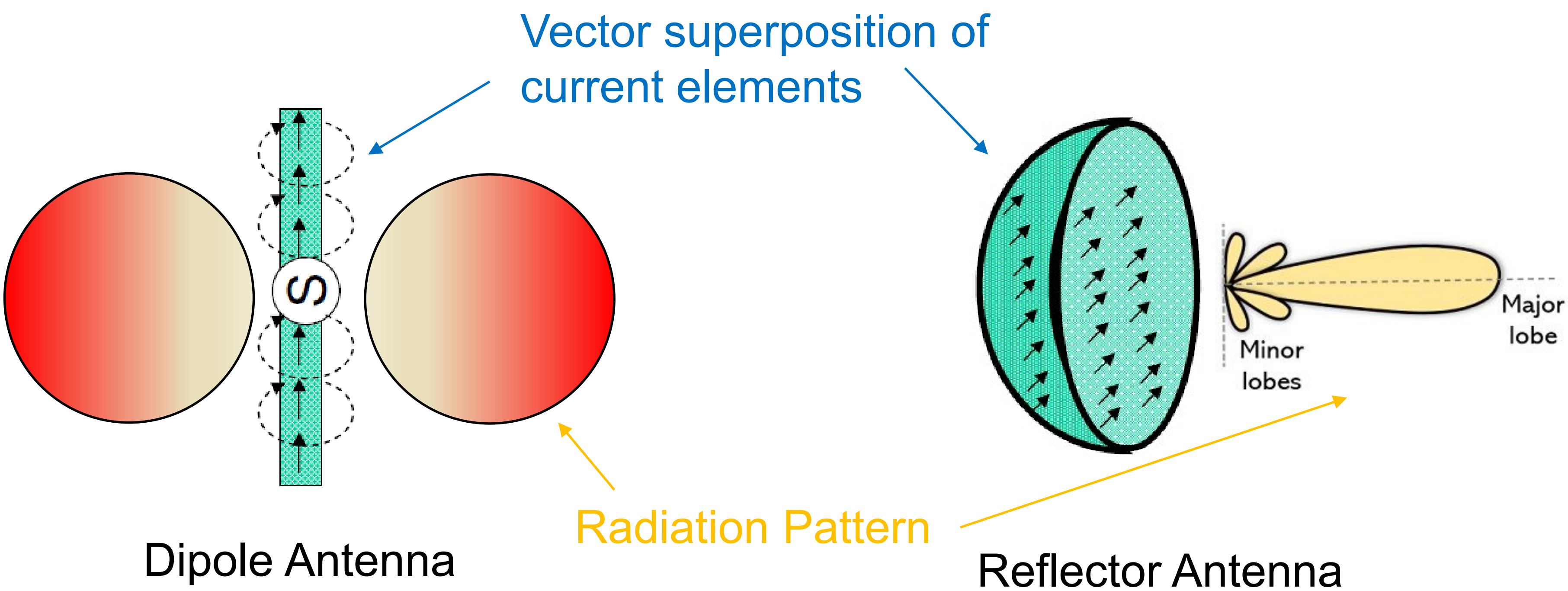
Electromagnetic (EM) field on aperture induces radiation

* Referenced Prof. Ethan Wang's and Prof. Yahya Rahmat-Samii's classes

How to Get Radiation Characteristic*

Q: Can we find the radiation performance of the antenna with given the distribution of time-varying current?

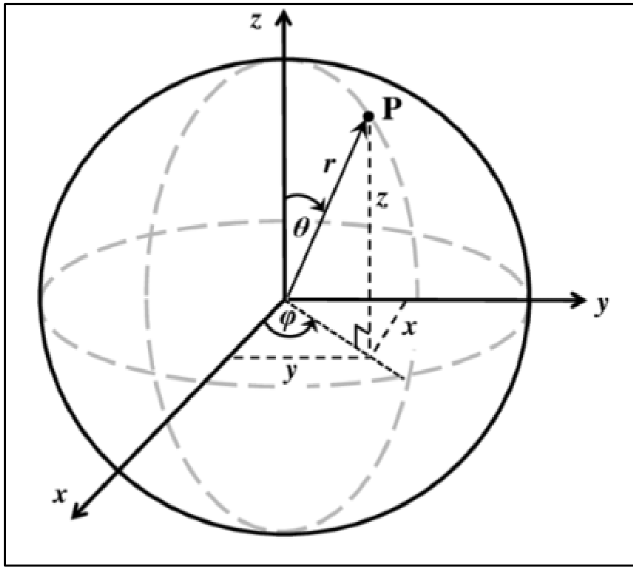
A: Antenna's radiation characteristic can be solved by the **vector superposition** of the elementary current elements.



* Referenced Prof. Ethan Wang's class

Short Dipole

Spherical Coordinate



$$x = r \sin\theta \cos\varphi$$

$$y = r \sin\theta \sin\varphi$$

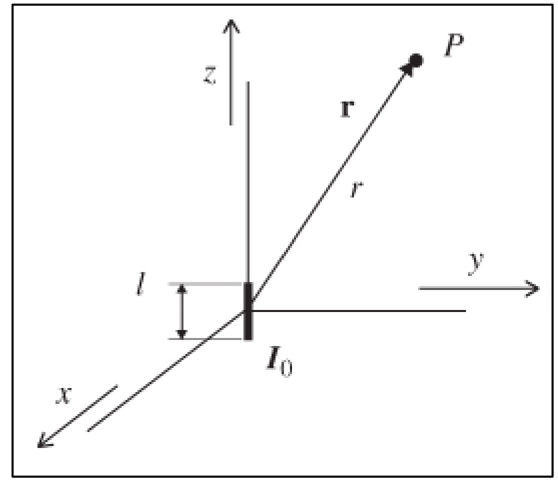
$$z = r \cos\theta$$

$$r = \sqrt{x^2 + y^2 + z^2}$$

$$\theta = \cos^{-1}(z/r)$$

$$\varphi = \tan^{-1}(y/x)$$

Short Dipole w/ AC Source [i(t)=I_0 cos ωt]



How to Solve Electromagnetic (EM) Field of Antenna

1. Find expression of antenna's current function
2. From the current function, calculate vector potential **A(r)** (**A(r),** extracted from Maxwell's eq.)
3. Find magnetic field **H** from the vector potential
4. Find electric field **E** from the magnetic field

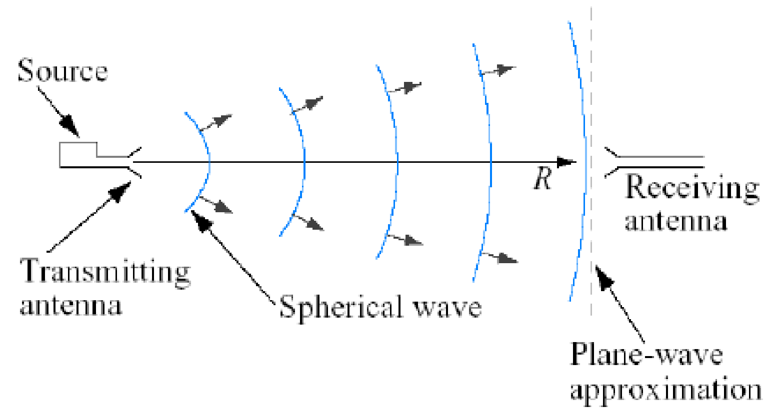
Short Dipole Electromagnetic Field

$$\begin{cases} E_R = \dfrac{I_0 l k^2}{2\pi}\eta_0 e^{-jkr}\left[\dfrac{1}{(kr)^2} - \dfrac{j}{(kr)^3}\right]\cos\theta \\[2ex] E_\theta = \dfrac{I_0 l k^2}{4\pi}\eta_0 e^{-jkr}\left[\dfrac{j}{kr} + \dfrac{1}{(kr)^2} - \dfrac{j}{(kr)^3}\right]\sin\theta \\[2ex] H_\phi = \dfrac{I_0 l k^2}{4\pi} e^{-jkr}\left[\dfrac{j}{kr} + \dfrac{1}{(kr)^2}\right]\sin\theta \end{cases}$$

$k=2\pi/\lambda$: free space wave number

Short Dipole*

$$\begin{cases} H_\phi = \dfrac{I_0 l k^2}{4\pi} e^{-jkR}\left[\dfrac{j}{kR} + \dfrac{1}{(kR)^2}\right]\sin\theta \\ E_R = \dfrac{2 I_0 l k^2}{4\pi}\eta_0 e^{-jkR}\left[\dfrac{1}{(kR)^2} - \dfrac{j}{(kR)^3}\right]\cos\theta \\ E_\theta = \dfrac{I_0 l k^2}{4\pi}\eta_0 e^{-jkR}\left[\dfrac{j}{kR} + \dfrac{1}{(kR)^2} - \dfrac{j}{(kR)^3}\right]\sin \end{cases}$$



When $R >> \lambda$, then $\dfrac{1}{R^2}, \dfrac{1}{R^3}$ terms are gone in the above expressions,

Therefore, we should have,

$$\begin{cases} E_\theta = \dfrac{jI_0 lk}{4\pi}\eta_0\left(\dfrac{e^{-jkR}}{R}\right)\sin\theta \\ H_\phi = \dfrac{jI_0 lk}{4\pi}\left(\dfrac{e^{-jkR}}{R}\right)\sin\theta = E_\theta / \eta_0 \end{cases}$$

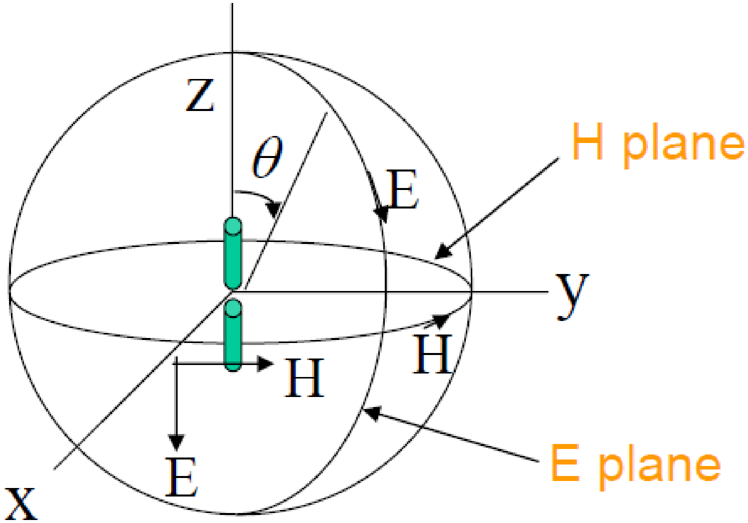
Radiation Pattern

Similar to plane waves!

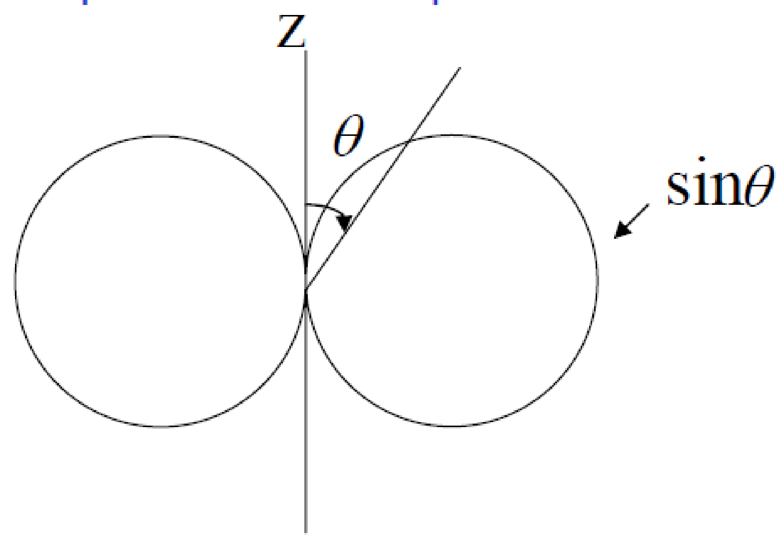
* From Prof. Ethan Wang's class

Radiation Pattern of Short Dipole*

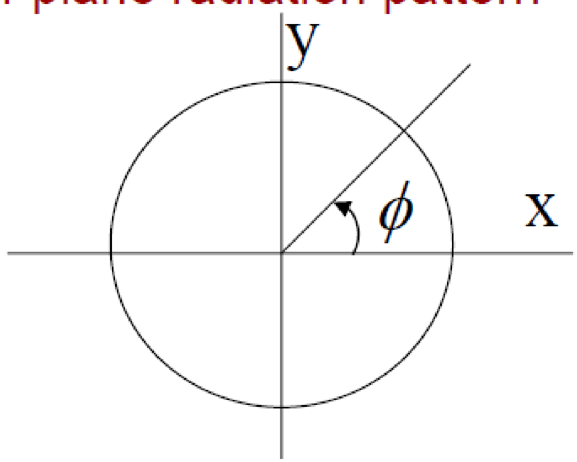
$$\begin{cases} E_\theta = \dfrac{jI_0 lk}{4\pi}\eta\left(\dfrac{e^{-jkr}}{r}\right)\sin\theta \\ H_\phi = \dfrac{jI_0 lk}{4\pi}\left(\dfrac{e^{-jkr}}{r}\right)\sin\theta = E_\theta / \eta_0 \end{cases}$$



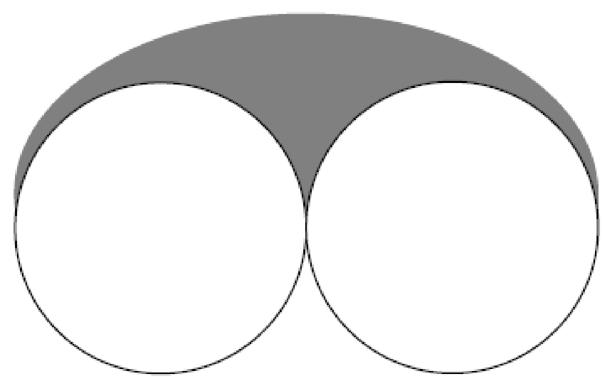
E-plane radiation pattern



H-plane radiation pattern



3-D view - "Donut" shape



* From Prof. Ethan Wang's class

Antenna Parameter: Pattern*

Normalized field pattern: $$F(\theta,\phi)=\frac{E_\theta}{E_\theta(\max)}$$

For infinitestimal dipole, $$F(\theta)=\frac{(Il/4\pi)\,j\omega\mu(e^{-jkr}/r)\sin\theta}{(Il/4\pi)\,j\omega\mu(e^{-jkr}/r)}=\sin\theta$$

$$F(\theta,\phi)=g(\theta,\phi)f(\theta,\phi)\quad\begin{cases} g(\theta,\phi) & \text{Element factor} \\ f(\theta,\phi) & \text{Pattern factor}\end{cases}$$

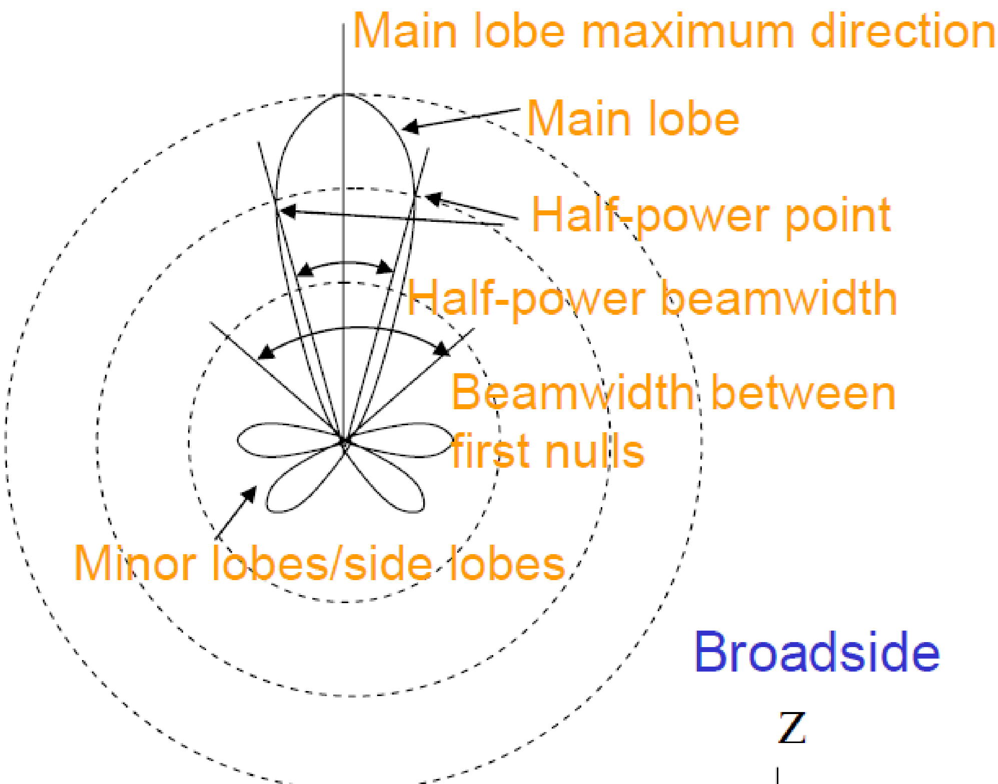
For z directed current element, $$g(\theta)=\sin\theta$$

Uniform line source pattern: $$f(\theta)=\frac{\sin[(kL/2)\cos\theta]}{(kL/2)\cos\theta}$$

Half-wave dipole pattern: $$f(\theta)=\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin^2\theta}$$

* From Prof. Ethan Wang's class

Antenna Parameter: Pattern*



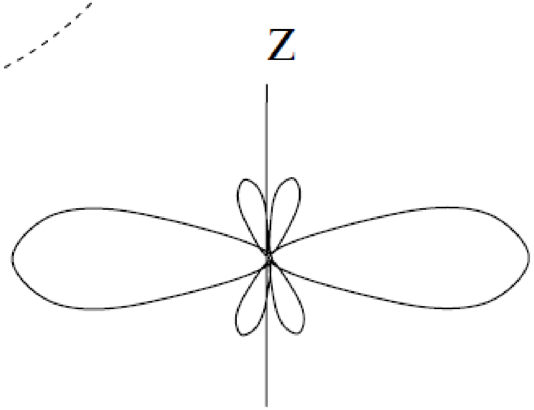
Side lobe level is defined as:

$$SLL_{dB} = 10\log\frac{|F(SLL)|}{|F(\max)|}$$

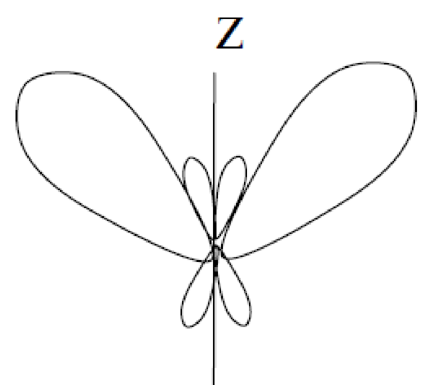
Half-power beamwidth:

$$HP = \left|\theta_{HPleft} - \theta_{HPright}\right|$$

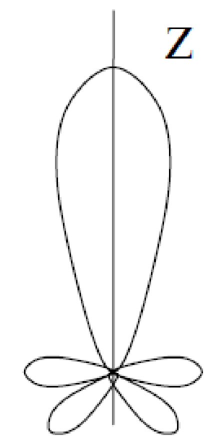
Broadside



Intermediate



Endfire



* From Prof. Ethan Wang's class

Antenna Parameter: Pattern*

Two principal planes:

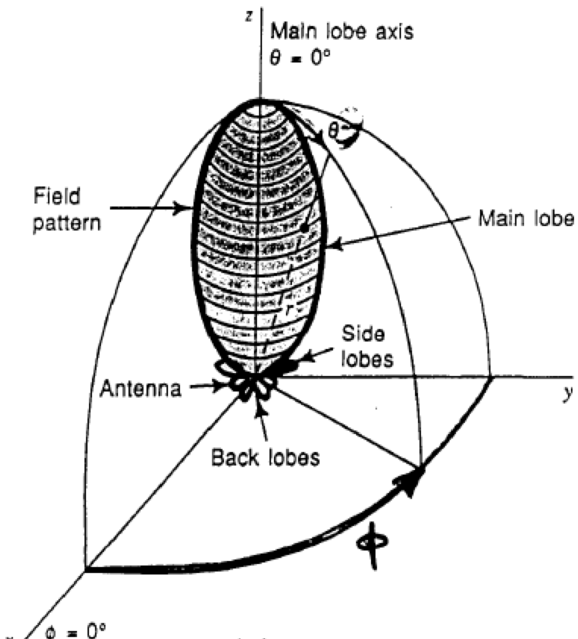
Θ plane: elevation plane

ϕ plane: azimuth plane

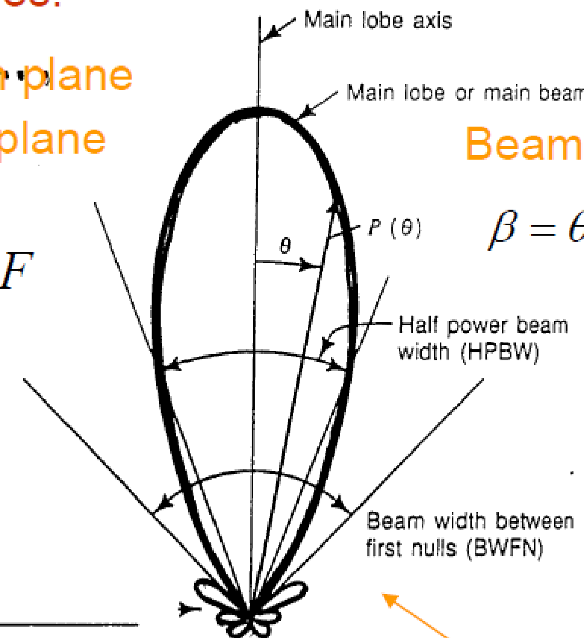
$$F(dB) = 10\log F$$

Beamwidth:

$$\beta = \theta_2 - \theta_1$$

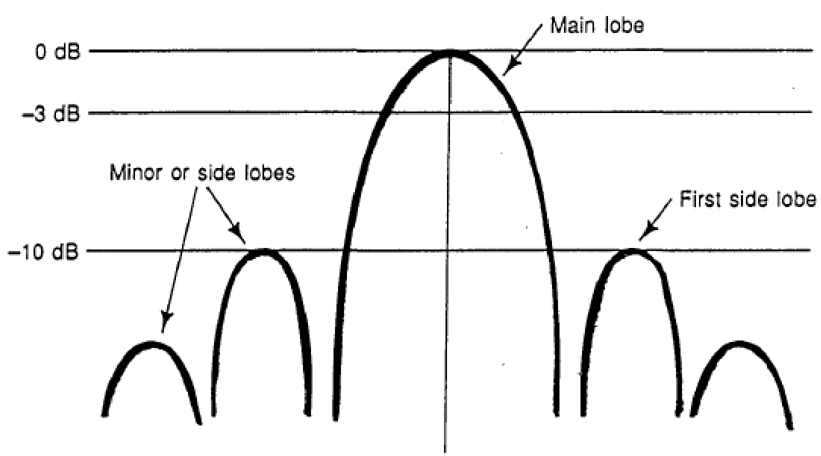


(a)



(b)

Polar form

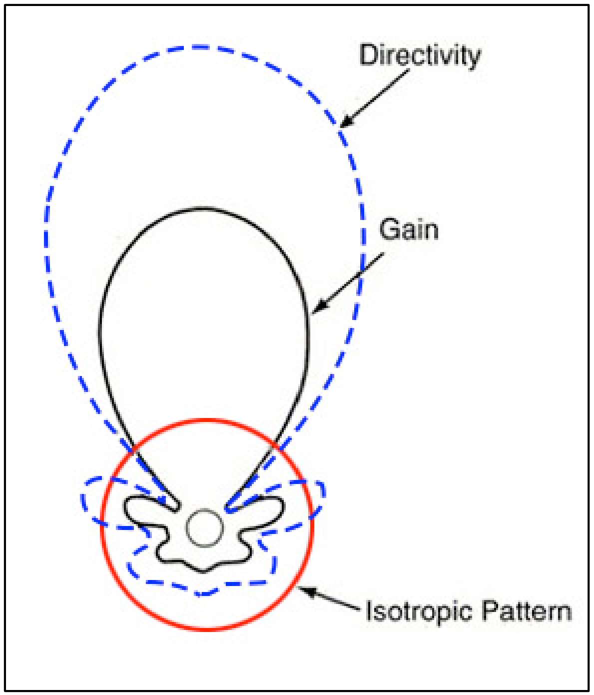


(c)

Rectangular form

* From Prof. Ethan Wang's class

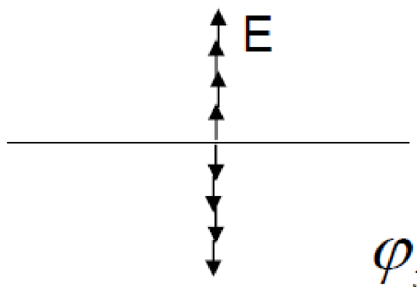
Antenna Parameter: Directivity & Gain



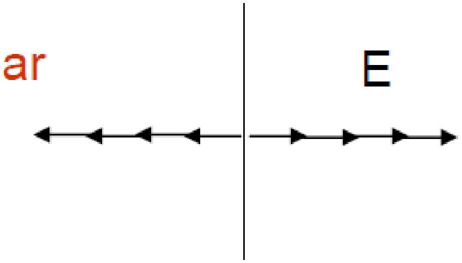
- Directivity is the ratio of maximum radiation density to the average density.
- Directivity of isotropic antenna: $D_{iso} = 1$, $D_{iso} = 0$ dBi
- Directivity of half-wave dipole: D = 1.64, D = 2.15 dBi
- Larger directivity means more directional beam pattern. Directivity is solely determined by the radiation pattern.
- Gain: In real systems, antennas have loss. Gain is directivity considering antenna loss.
- With radiation efficiency $e_r = P_{rad}/P_{in}$, $\mathbf{G = e_r \cdot D}$
- Typical antennas have dielectric loss and conductive loss.

Antenna Parameter: Polarization*

Vertical linear Pol.

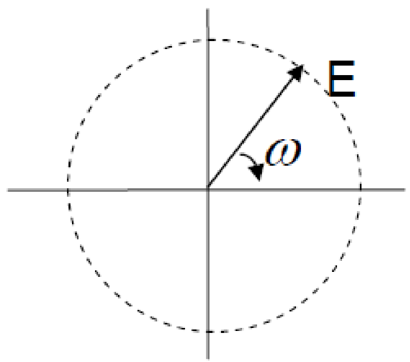


Horizontal linear Pol.

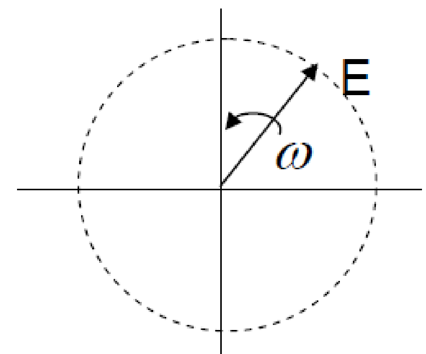


$$\varphi_x = \varphi_y = \varphi$$

Left-handed circular Pol.



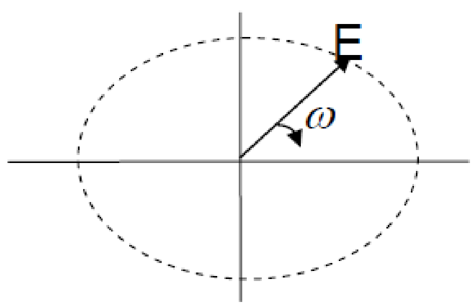
Right-handed circular Pol.



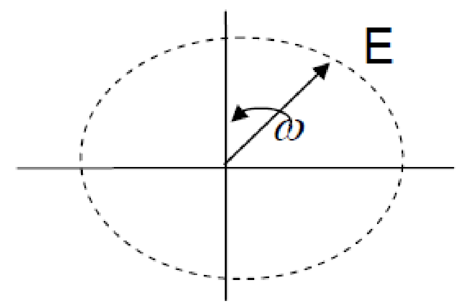
$$\varphi_y = \varphi_x + \frac{\pi}{2}, \quad \left|\tilde{E}_x\right| = \left|\tilde{E}_y\right|$$

$$\varphi_y = \varphi_x - \frac{\pi}{2}, \quad \left|\tilde{E}_x\right| = \left|\tilde{E}_y\right|$$

Left-handed elliptical Pol.



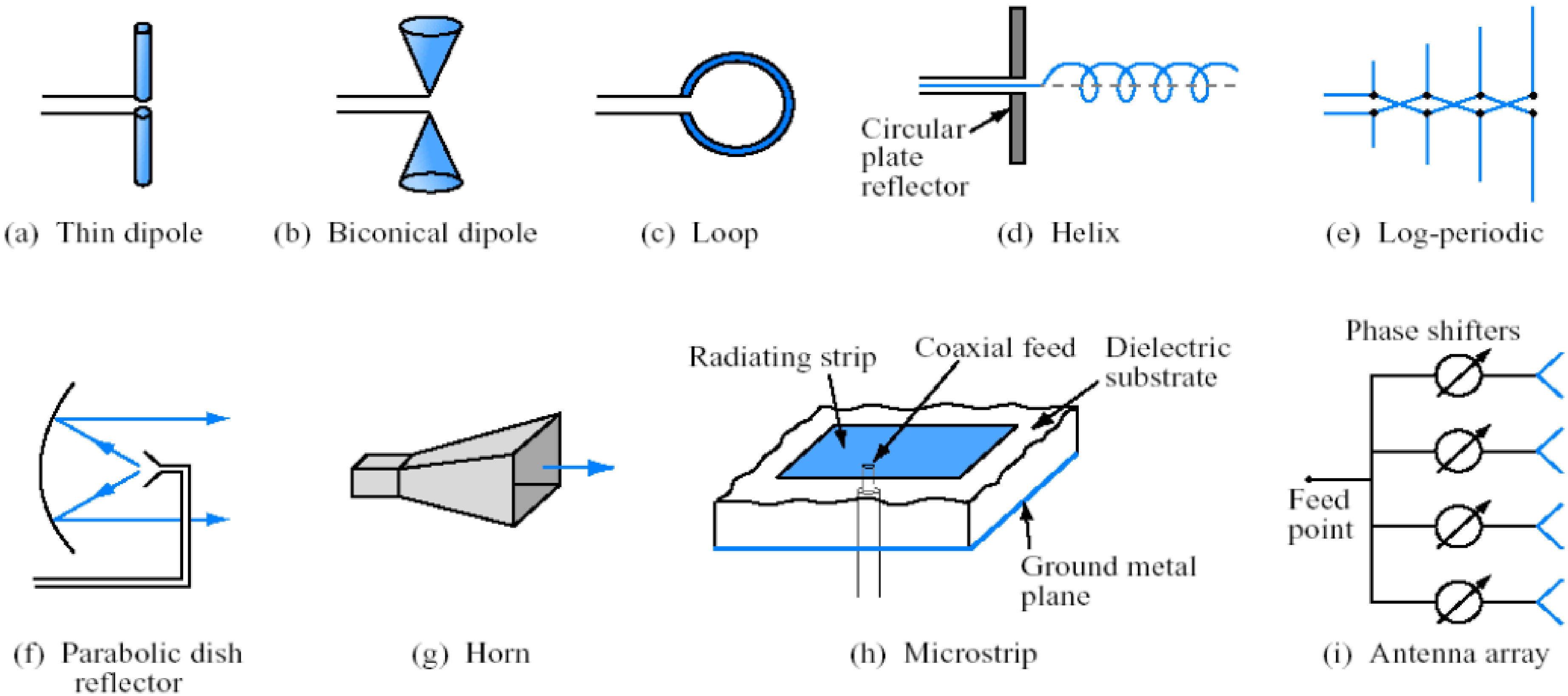
Right-handed elliptical Pol.



* From Prof. Ethan Wang's class

Antenna Applications

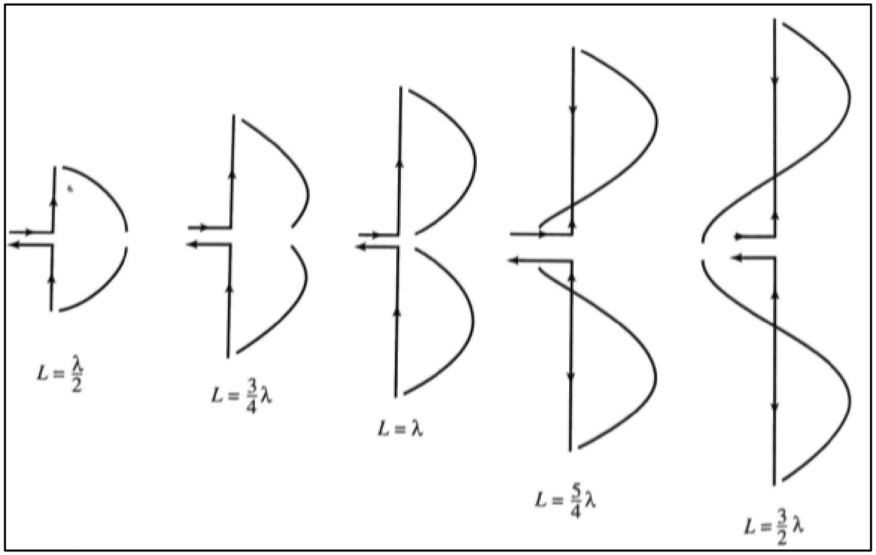
Various Type of Antennas*



* From Prof. Ethan Wang's class

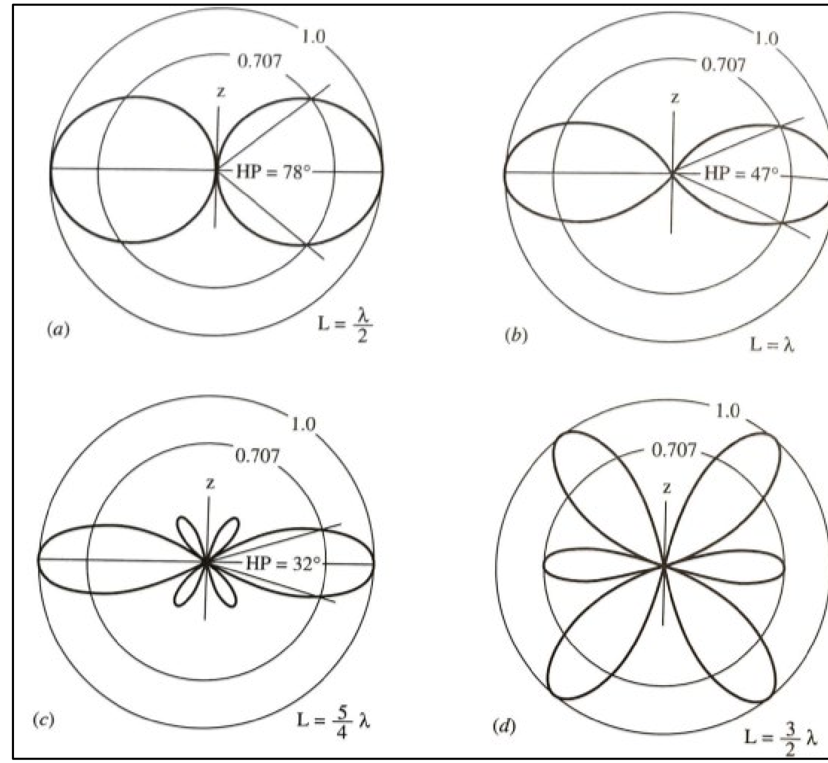
Ham Radio: Dipole Antenna*

Various Length of Dipoles



Arrows indicate relative current directions for maximum current conditions.

Radiation Patterns of Various Dipoles

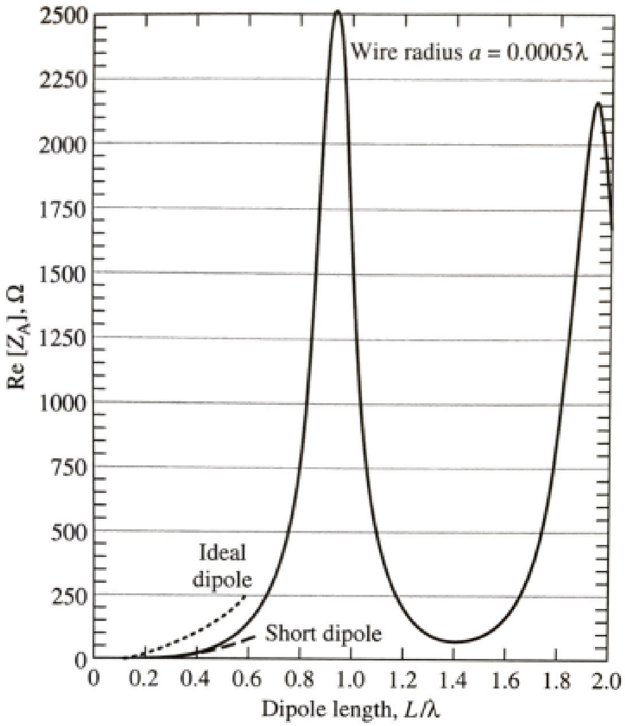


- **Larger than one wavelength of dipole produces multiple lobes that are not typically preferred.**
- **Radiation pattern of longer dipole shows narrower beam-width.**

* From "Antenna Theory and Design" book

Ham Radio: Dipole Antenna*

Input Resistance of Dipole Antenna as Function of Length



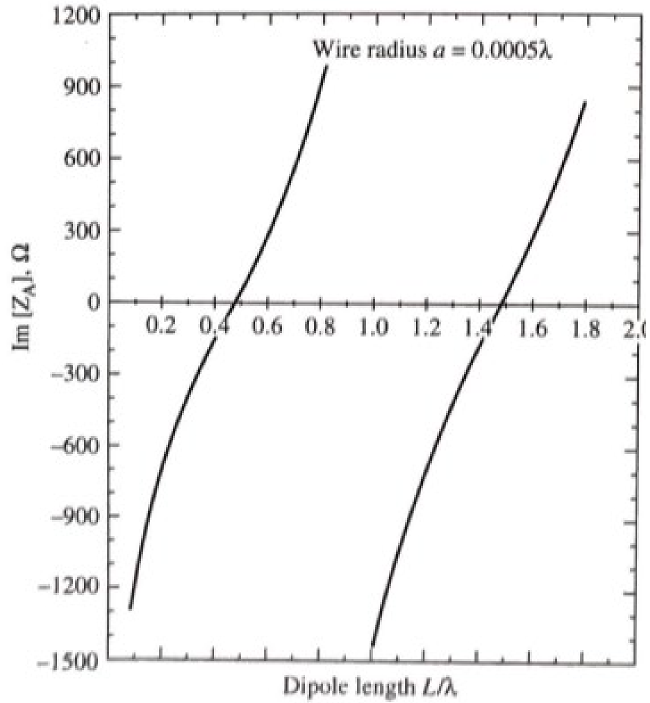


Table 5-1 Simple Formulas for the Input Resistance of Dipoles

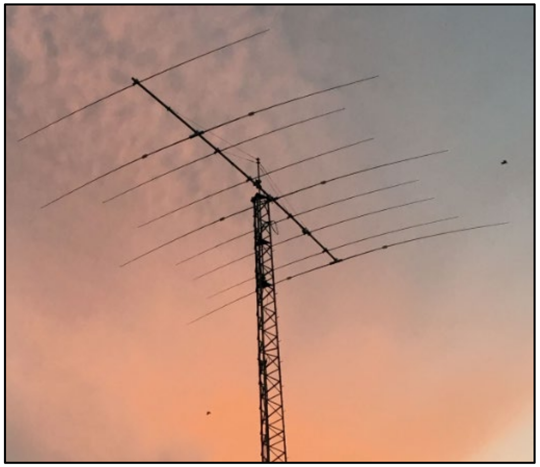
Length L	Input Resistance (R_{ri}), Ω
$0 < L < \frac{\lambda}{4}$	$20\pi^2\left(\frac{L}{\lambda}\right)^2$
$\frac{\lambda}{4} < L < \frac{\lambda}{2}$	$24.7\left(\pi\frac{L}{\lambda}\right)^{2.4}$
$\frac{\lambda}{2} < L < 0.637\lambda$	$11.14\left(\pi\frac{L}{\lambda}\right)^{4.17}$

Typical ham radio transceivers require 50 ohm input impedance of antenna. If your antenna does not provide 50 ohm impedance, additional matching will be required for increasing communication distance.

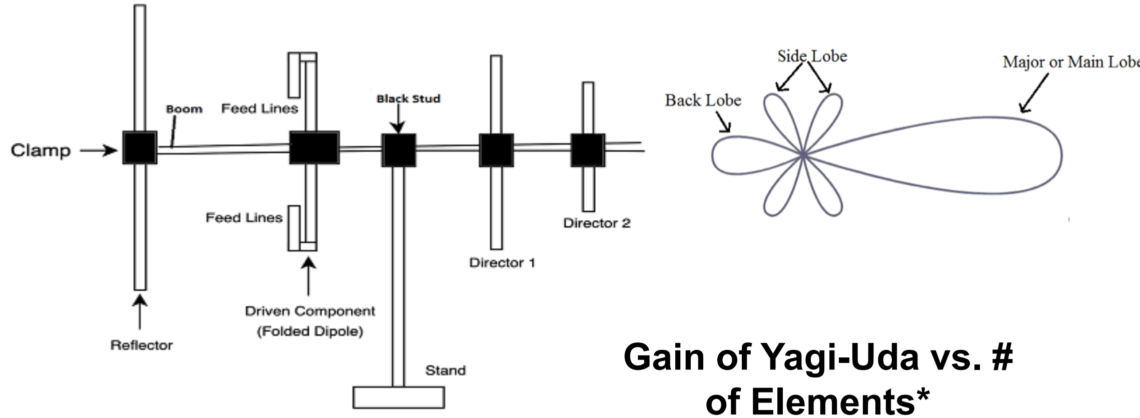
* From "Antenna Theory and Design" book

Ham Radio: Yagi-Uda Antenna*

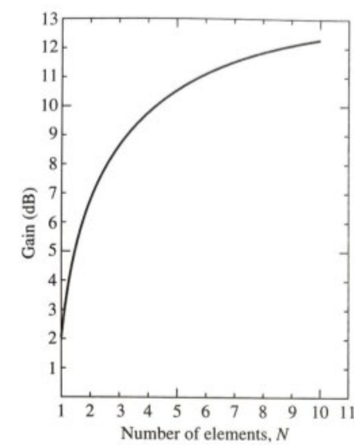
Ham Radio HF Yagi Antenna



Yagi-Uda Antenna Structure and Radiation Pattern

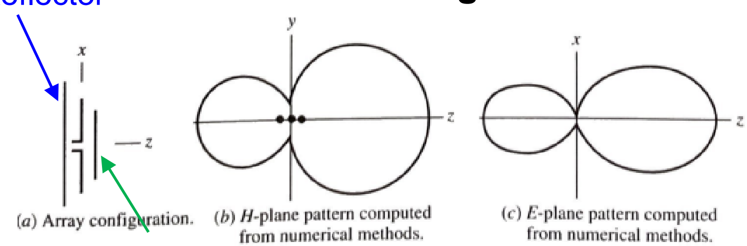


Gain of Yagi-Uda vs. # of Elements*



Three Element Yagi-Uda*

Reflector



(a) Array configuration. (b) H-plane pattern computed from numerical methods. (c) E-plane pattern computed from numerical methods.

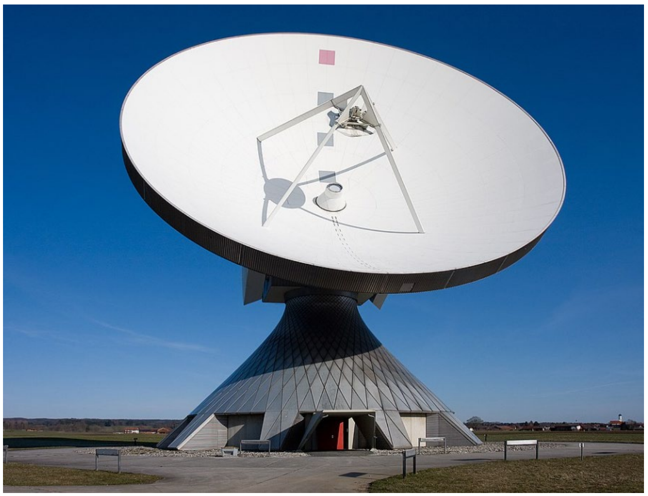
Director

Yagi-Uda antenna provide more direction beam (higher antenna gain) with simple configuration. Therefore, this type of antenna is commonly used in Ham Radio.

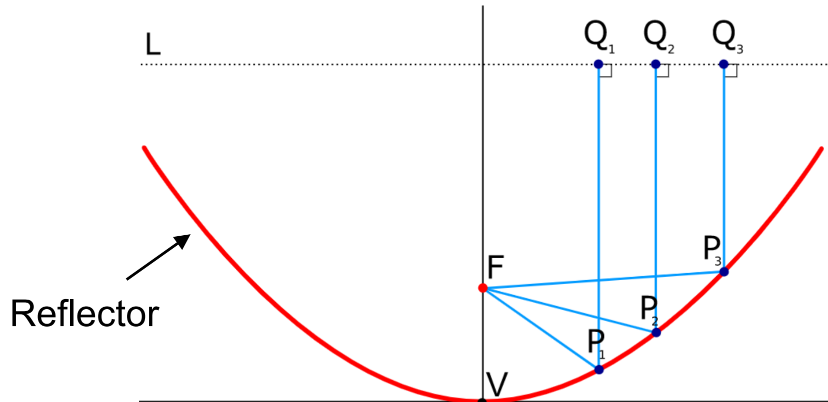
* From “Antenna Theory and Design” book

Satellite Comm.: Reflector Antenna*

Parabolic Satellite Comm. Antenna in Germany

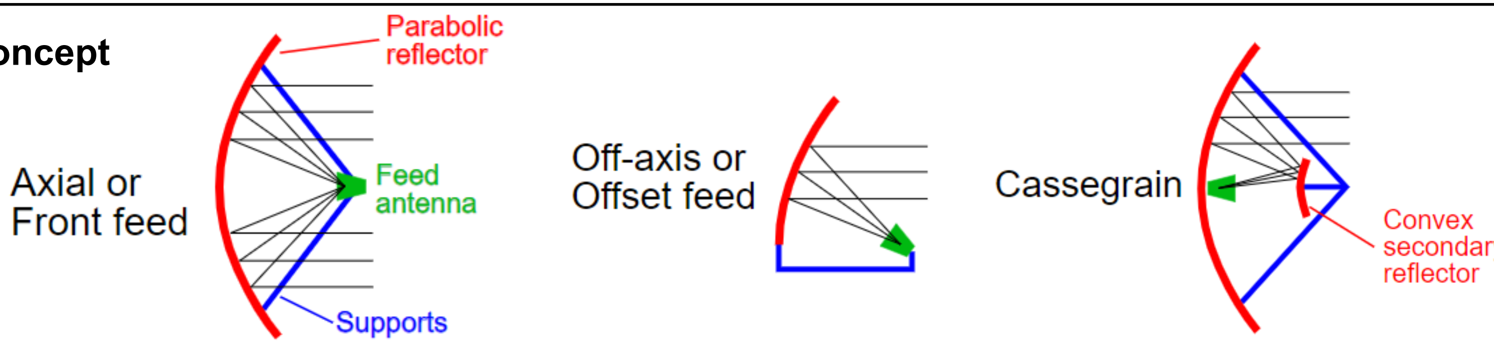


Operation Concept



Reflector geometry provides $FP_1Q_1 = FP_2Q_2 = FP_3Q_3$. Thus, a spherical wavefront emitted by a feed antenna at the dish's focus *F* will be reflected into an outgoing plane wave *L* travelling parallel to the dish's axis *VF*.

Various Feeding Concept

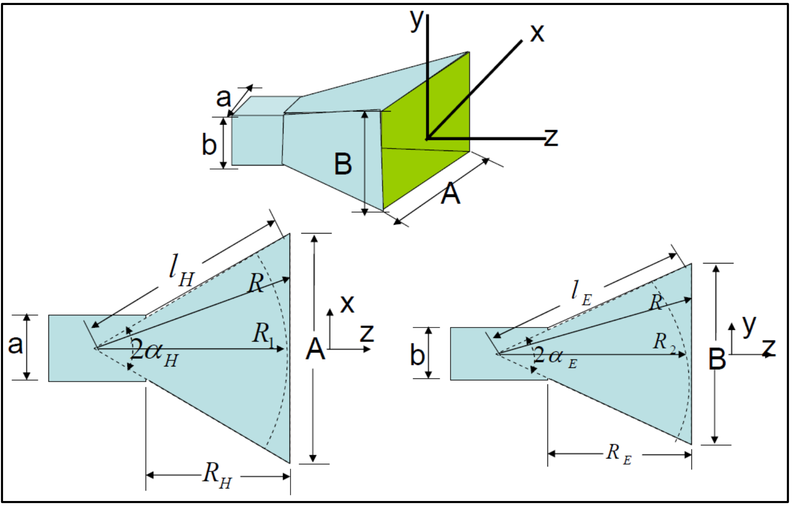


Reflector antennas provide very high gain (> 50dBi) and narrow beam. Therefore, it is suitable for satellite communication systems.

* From Wikipedia

Satellite Comm.: Reflector Antenna Feed Horn*

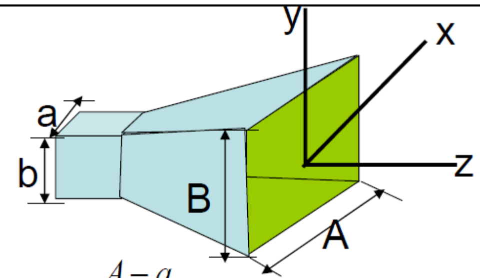
Pyramidal Horn Antenna Dimensions



Design Equation

Physical constraints:

$$\begin{cases} R_E = R_H = R_P \\ R_1 / R_H = A/(A-a) \\ R_2 / R_E = B/(B-b) \end{cases}$$



For optimum horn, $B = \frac{1}{2}(b + \sqrt{b^2 + 8\lambda R_E})$ $\quad R_E = \frac{A-a}{3\lambda} A$

$$G = \frac{4\pi}{\lambda^2}\varepsilon_{ap} AB = \frac{4\pi}{\lambda^2}\varepsilon_{ap} A \frac{1}{2}\left(b + \sqrt{b^2 + \frac{8A(A-a)}{3}}\right)$$

⇩

$$A^4 - aA^3 + \frac{3bG\lambda^2}{8\pi\varepsilon_{ap}} A = \frac{3G^2\lambda^4}{32\pi^2\varepsilon_{ap}^2}$$

optimum pyramidal horn design equation

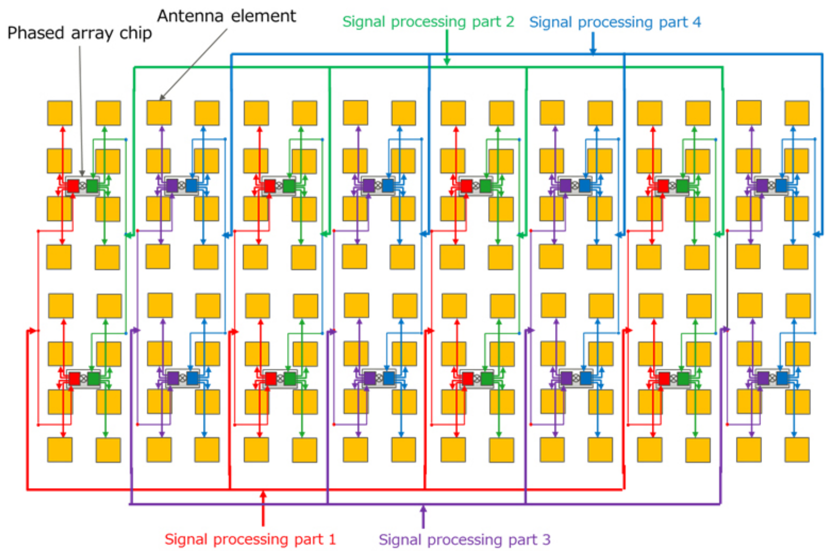
Known *a*,*b*,*G*, how to design the horn?

Horn antennas are well established technology and predictable. They are mainly used for feedings of reflector antennas or measurement equipments.

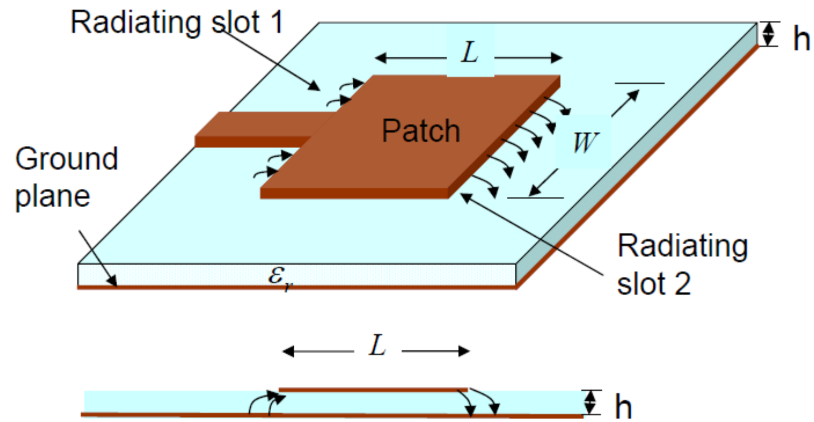
* From Prof. Ethan Wang's class

5G Comm.: Patch Antenna

Fujitsu 28 GHz, 4-Beam, 128-Element Phased Array Antenna



Patch Antenna Radiation Mechanism



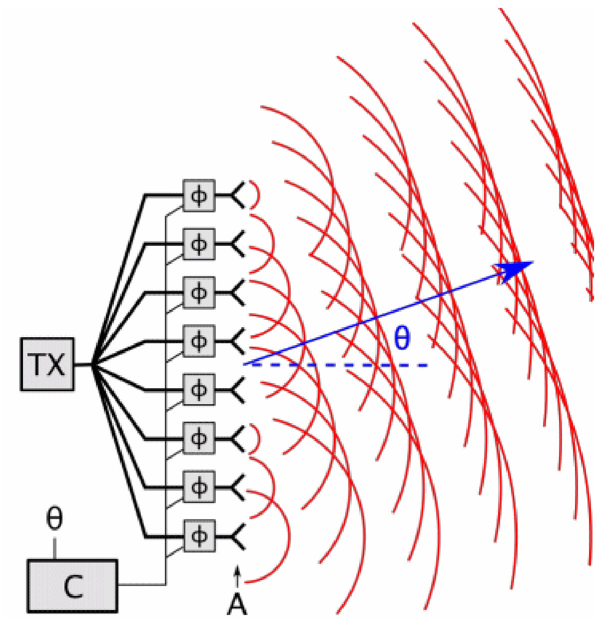
Prof. Ethan Wang's class material

- Radiation comes from slots on edges.
- Fringing fields on two edges are in phase.

Because of the simplicity and conformality, patch antennas are used in various communication systems including airborne, vehicle, cell phone, body-worn, satellite, and etc..

Antenna Array

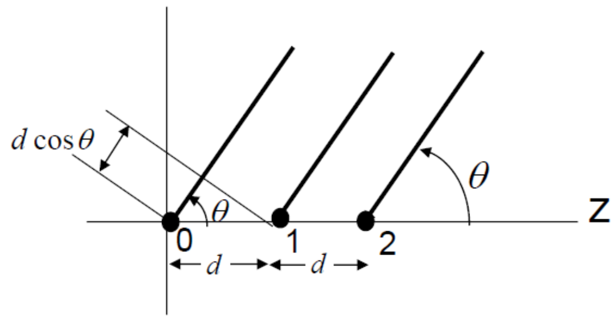
Phased Antenna Array*



Linear Array Antenna Calculation**

In general, the array factor is $AF = I_0 + I_1 e^{j\beta d\cos\theta} + I_2 e^{j\beta 2d\cos\theta} + \cdots = \sum_{0}^{N-1} I_n e^{j\beta n d\cos\theta}$

For linear phase progression,



$$I_n = A_n e^{jn\alpha},$$

$$AF = \sum_{n=0}^{N-1} A_n e^{jn(\beta d\cos\theta + \alpha)}$$

Define $\psi = \beta d\cos\theta + \alpha$

Then $AF = \sum_{n=0}^{N-1} A_n e^{jn\psi}$

Pattern from aperture antennas: Fourier Integration

Pattern from antenna arrays: Fourier series

You can control antenna's gain and pattern with antenna arrays. Electrically controlled beam scanning and shaping are also available.

* From Wikipedia

* * From Prof. Ethan Wang's class

Q & A