



I ILLINOIS

Electrical & Computer Engineering

GRAINGER COLLEGE OF ENGINEERING

Antenna for EMC

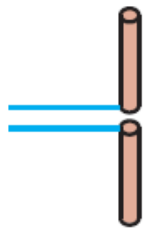
Prof. Victoria Shao

Introduction

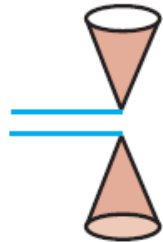
1. Antenna Overview
2. Ideal Dipole (Hertzian Dipole)
3. Antenna parameters
4. Dipole and Monopole
5. Other Antennas
6. Antenna Arrays
7. Antennas in communication systems



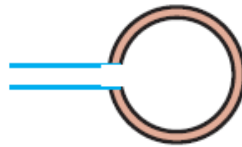
1 Antenna Overview



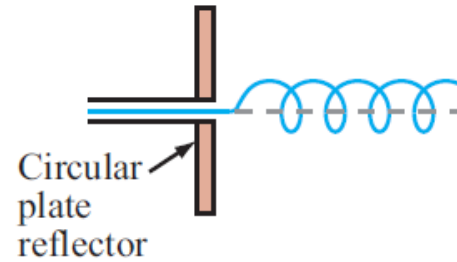
(a) Thin dipole



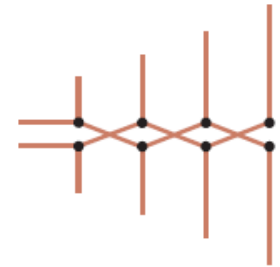
(b) Biconical dipole



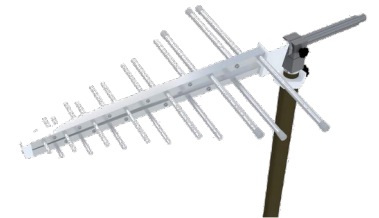
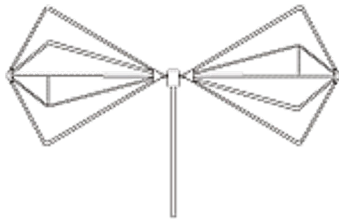
(c) Loop



(d) Helix

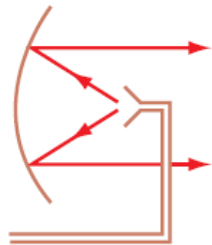


(e) Log-periodic

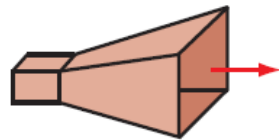


Examples of Antennas

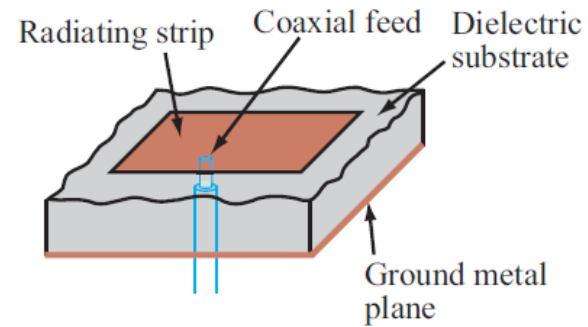
1 Antenna Overview



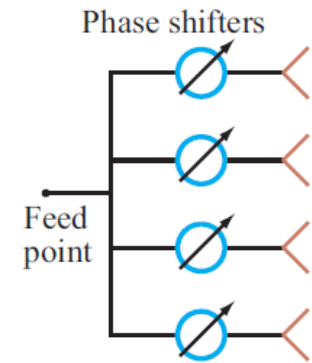
(f) Parabolic dish reflector



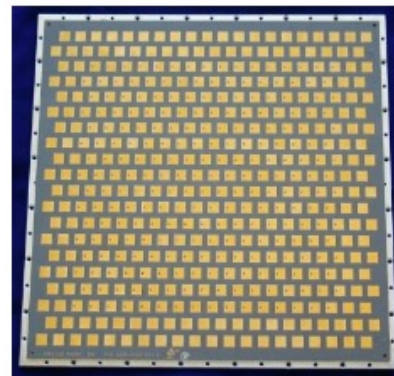
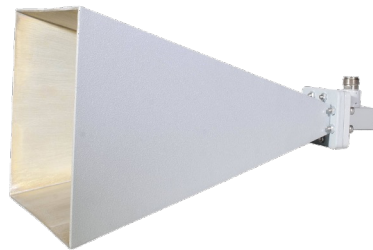
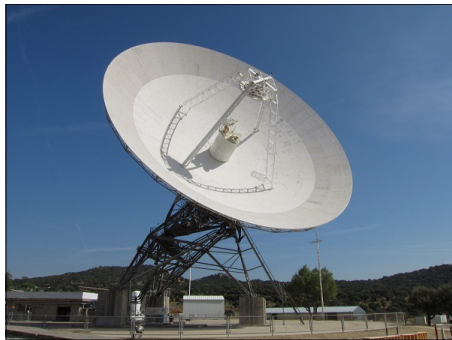
(g) Horn



(h) Microstrip



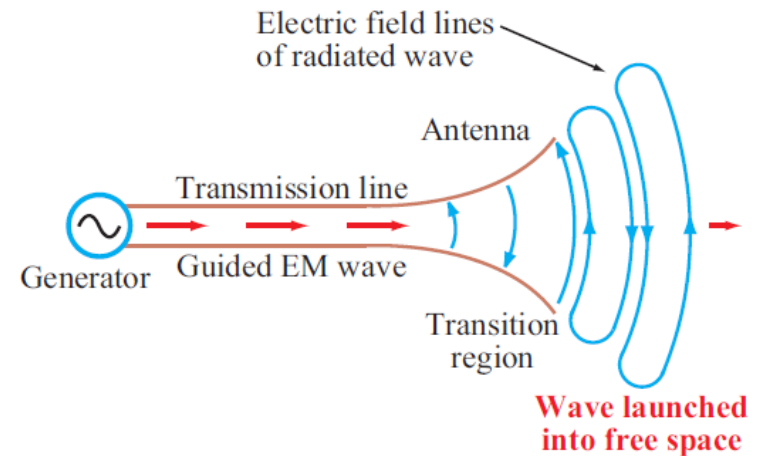
(i) Antenna array



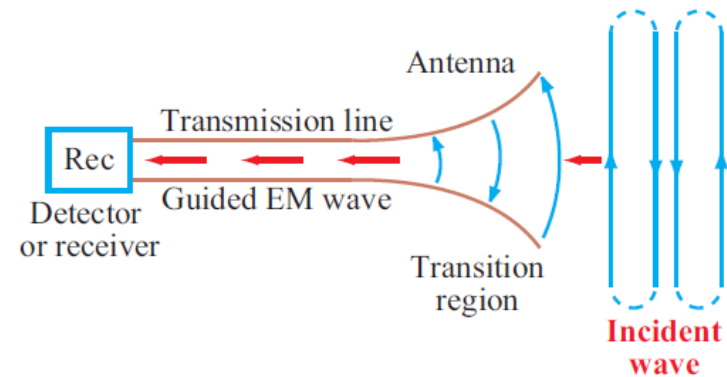
Examples of Antennas

Antenna Properties

1. An antenna is a **transducer** that converts a guided wave propagating on a transmission line into an electromagnetic wave propagating in an unbounded medium (usually free space), or vice versa.
2. Most antennas are **reciprocal devices**, exhibiting the same radiation pattern for transmission as for reception.
3. Being a reciprocal device, an antenna, when operating in the receiving mode, can extract from an incident wave only that component of the wave whose electric field matches the **antenna polarization** state.



(a) Transmission mode

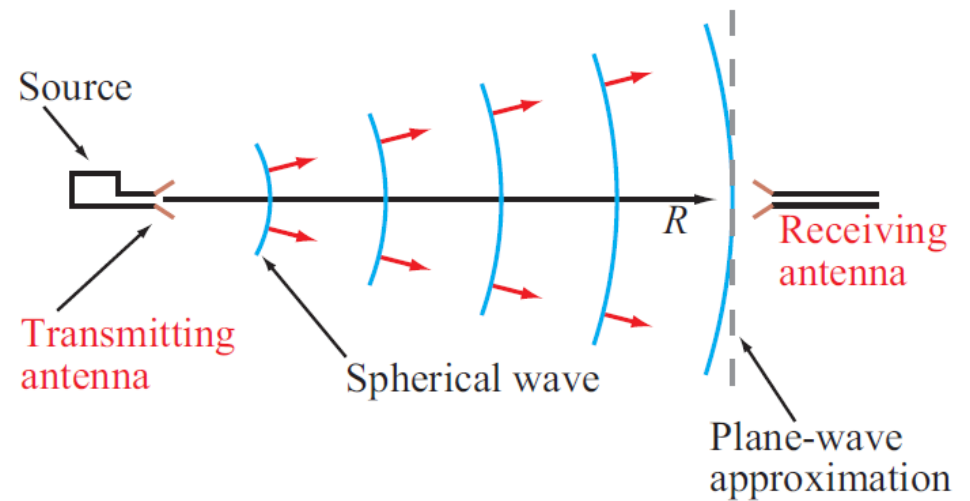


(b) Reception mode

Antenna as a transducer between a guided electromagnetic wave and a free-space wave, for both transmission and reception.

Far-Field Approximation

1. In close proximity to a radiating source, the wave is **spherical** in shape, but at a far distance, it becomes approximately a **plane wave** as seen by a receiving antenna.
2. The far-field approximation **simplifies the math**.
3. The distance beyond which the far-field approximation is valid is called the **far-field range** (will be defined later).



Far-field plane-wave approximation.

Steps in evaluation of radiation fields :

(Solution of Maxwell equations for radiation problems)

Vector wave equation → $\nabla^2 \vec{A} + \omega^2 \mu \epsilon \vec{A} = -\mu \vec{J}$

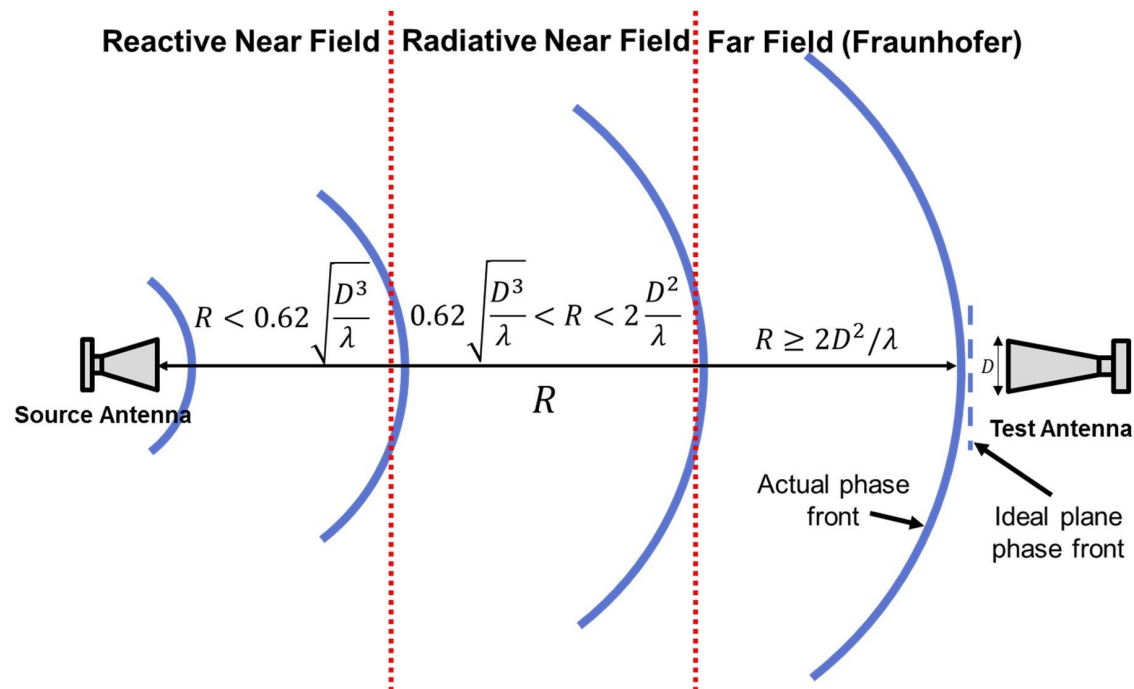
Solution is

$$\vec{A} = \iiint_{v'} \mu \vec{J} \frac{e^{-j\beta R}}{4\pi R} dv'$$

General approach to solve for radiation problem:

1. Calculate vector potential $\vec{A}$
2. Find magnetic field $\vec{H} = \frac{1}{\mu} \nabla \times \vec{A}$
3. Calculate the $\vec{E}$ field by Ampere's Law $\vec{E} = \frac{1}{j\epsilon\omega} \nabla \times \vec{H}$
Far field (Plane wave) $\vec{E} = \eta \vec{H} \times \hat{k}$

Far-Field Conditions



D is the length of line source

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

D is the dimension of surface source

$$r \gg D$$

2 The ideal dipole (Hertzian dipole)

Definition: A *Hertzian dipole* is a thin, linear conductor whose length l is very short compared with the wavelength λ ; l should not exceed $\lambda/50$.

Current along dipole:

$$i(t) = I_0 \cos \omega t = \Re[I_0 e^{j\omega t}]$$

Solution of E and H field at R distance away

$$\tilde{H}_\phi = \frac{I_0 l k^2}{4\pi} e^{-jkR} \left[\frac{j}{kR} + \frac{1}{(kR)^2} \right] \sin \theta, \quad (1)$$

$$\tilde{E}_R = \frac{2I_0 l k^2}{4\pi} \eta_0 e^{-jkR} \left[\frac{1}{(kR)^2} - \frac{j}{(kR)^3} \right] \cos \theta, \quad (2)$$

$$\tilde{E}_\theta = \frac{I_0 l k^2}{4\pi} \eta_0 e^{-jkR} \left[\frac{j}{kR} + \frac{1}{(kR)^2} - \frac{j}{(kR)^3} \right] \sin \theta$$

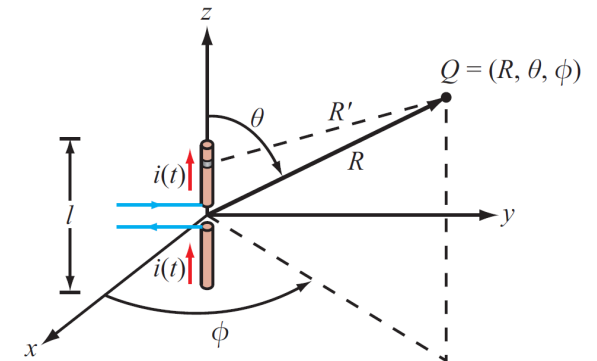


Figure 9-4: Short dipole placed at the origin of a spherical coordinate system.

k or β : wave number $k = \frac{2\pi}{\lambda}$

dipole antennas are commonly used for both emission and immunity testing

Hertzian Dipole—Far-Field Approximation

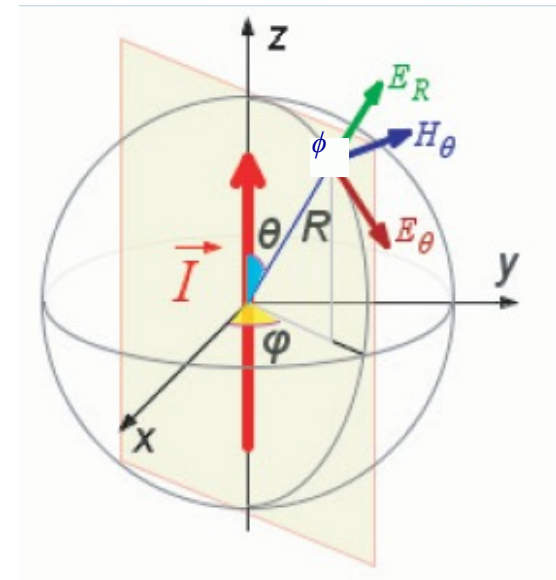
At far field regions

$$\tilde{E}_\theta = \frac{j I_0 l k \eta_0}{4\pi} \left(\frac{e^{-jkR}}{R} \right) \sin \theta \quad (\text{V/m}),$$

$$\tilde{H}_\phi = \frac{\tilde{E}_\theta}{\eta_0} \quad (\text{A/m}),$$

$\frac{e^{-jkR}}{R}$:spherical propagation factor

$\eta_0 = 120\pi \Omega$ intrinsic impedance of the medium



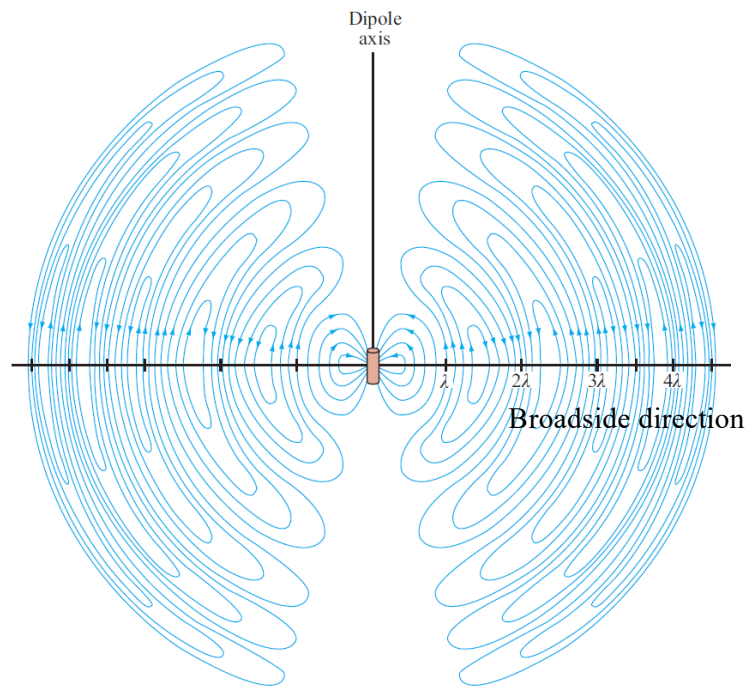
$$\vec{H} = \frac{I \Delta z}{4\pi} j \omega \mu \frac{e^{-j\beta r}}{r} \sin \theta \hat{\phi}$$

$$\vec{E} = \frac{I \Delta z}{4\pi} j \beta \frac{e^{-j\beta r}}{r} \sin \theta \hat{\theta}$$

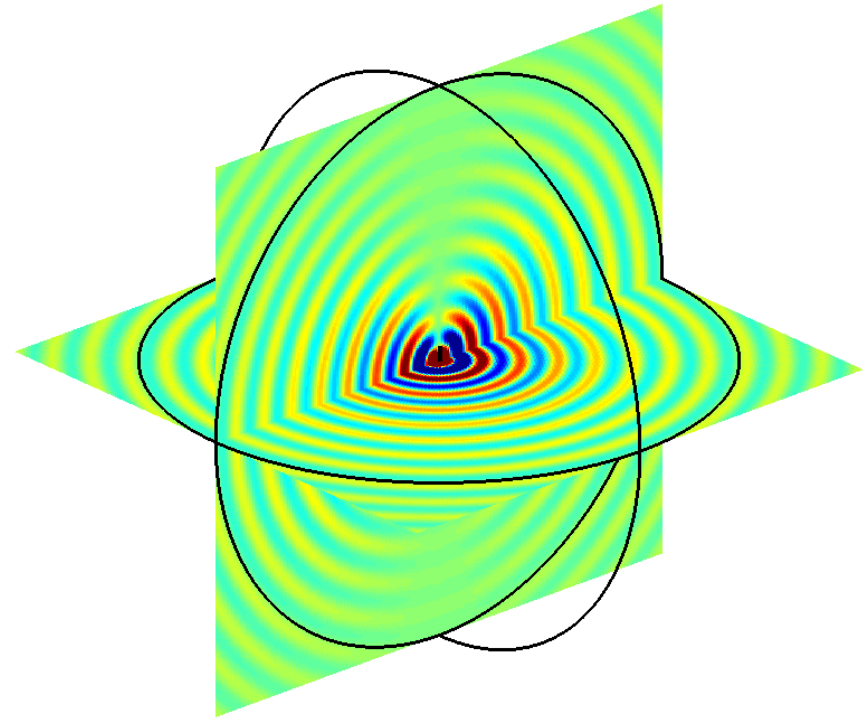
Ω

I

Radiated Electric Field



Electric field lines surrounding an oscillating dipole at a given instant.



The ideal dipole (Hertzian dipole): Far-Field Properties

1. The fields are proportional to $1/r$, $\hat{l}$, dl , and $\sin \theta$.
2. $|\vec{E}_{\text{far field}}|/|\vec{H}_{\text{far field}}| = \eta_0$.
3. $\vec{E}_{\text{far field}}$ and $\vec{H}_{\text{far field}}$ are *locally orthogonal*.
4. $\vec{E}_{\text{far field}} \times \vec{H}_{\text{far field}} = K\vec{a}_r$.
5. A phase term $e^{-j\beta_0 r}$ translates to a time delay in the time domain of $\sin[\omega(t - r/v_0)]$.

$$\vec{H} = \frac{I\Delta z}{4\pi} j\omega\mu \frac{e^{-j\beta r}}{r} \sin\theta \hat{\phi}$$

$$\vec{E} = \frac{I\Delta z}{4\pi} j\beta \frac{e^{-j\beta r}}{r} \sin\theta \hat{\theta}$$

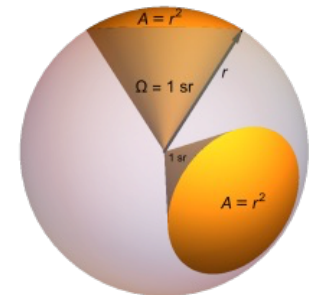
Power flowing density : (Unit : w/m*m)

$$\vec{S} = \frac{1}{2} \vec{E} \times \vec{H}^* = \frac{1}{2} \left(\frac{I\Delta z}{4\pi} \right)^2 \omega\mu\beta \frac{\sin^2 \theta}{r^2} \hat{r} \quad \text{per unit solid angle}$$

Total radiated power (Unit : W)

$$P = \iint \vec{S} \cdot d\vec{s} = \iint \vec{S} r^2 \sin\theta d\theta d\phi$$

$$P = 80\pi^2 \left(\frac{\Delta z}{\lambda} \right)^2 \frac{I^2}{2}$$



$$d\Omega = \frac{dA}{r^2} = \sin\theta d\theta d\phi$$

solid angle



The ideal dipole (Hertzian dipole): Far-Field Properties

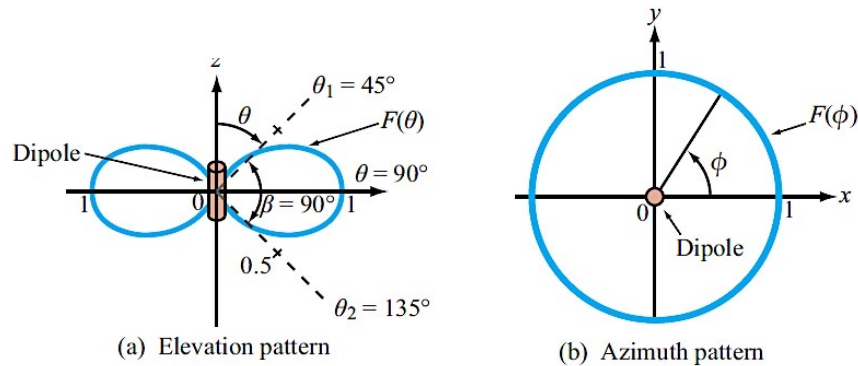
Denoting $\hat{I}/\sqrt{2} = \hat{I}_{\text{rms}}$, we can compute a **radiation resistance**:

$$R_{\text{rad}} = \frac{P_{\text{rad}}}{|\hat{I}_{\text{rms}}|^2} \\ = 80\pi^2 \left(\frac{dl}{\lambda_0} \right)^2 \quad (\text{in } \Omega)$$

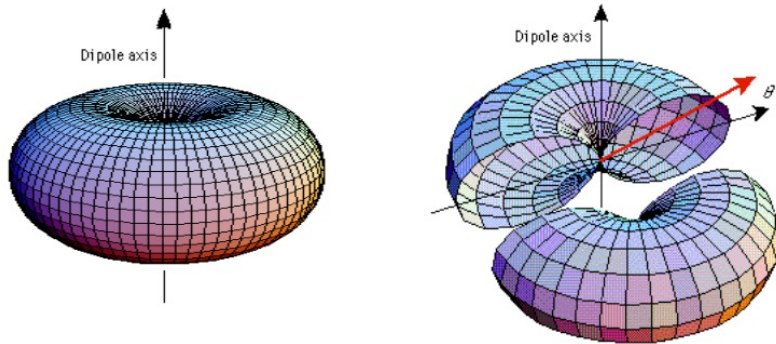
- The **radiation resistance** represents a fictitious resistance that dissipates the same amount of power as that radiated by the antenna when both carry the same value of current.
- The Hertzian dipole is a very ineffective radiator!
 - For example, for a length $dl = 1$ cm and a frequency of 300 MHz ($\lambda_0 = 1$ m), the radiation resistance is 79 m Ω . $\rightarrow$ In order to radiate 1 W of power, we require a (RMS) current of 3.6 A!
 - If the frequency is changed to 3 MHz ($\lambda_0 = 100$ m), the radiation resistance is 7.9 m Ω and the current (RMS) required to radiate 1 W is 356 A!



The ideal dipole (Hertzian dipole): Far-Field Properties



Radiation patterns of Hertzian dipole.



$$F(\theta, \phi) = \sin^2 \theta$$

Normalized Radiation Intensity

- describes the directional pattern of the antenna

$$F(\theta, \phi) = \frac{S(R, \theta, \phi)}{S_{\max}} \quad \text{dimensionless}$$

For Hertzian dipole

$$F(\theta, \phi) = F(\theta) = \sin^2 \theta$$

- No energy is radiated by the short dipole along the direction of the dipole axis
- Maximum radiation ($F=1$) occurs in the broadside direction ($\theta=90^\circ$)

Hertzian Dipole Example

1. Compute the total power radiated by a 1-m long Hertzian dipole at 5 MHz, if the driving current amplitude is 5 A. Assume that the antenna operates in air.

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{5 \times 10^6} = 60 \text{ m}$$

$$P_{rad} = 40\pi^2 I_0^2 \left(\frac{l}{\lambda} \right)^2 = 40\pi^2 5^2 \left(\frac{1}{60} \right)^2 = 2.74 \text{ W}$$

2. Compute the radiation resistance of the antenna from the previous example.

$$P_{rad} = \frac{1}{2} I_0^2 R_{rad}$$

$$R_{rad} = 80\pi^2 \left(\frac{l}{\lambda} \right)^2 = 80\pi^2 \left(\frac{1}{60} \right)^2 = 0.22 \Omega$$

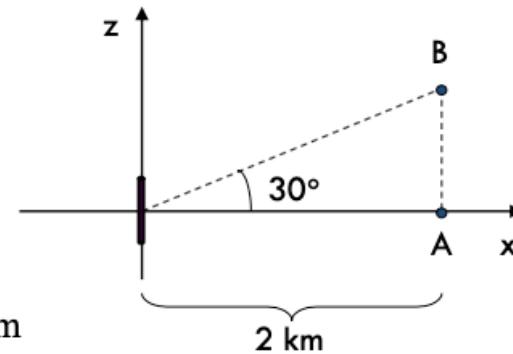
Hertzian Dipole Example

3. Consider the antenna from the previous examples and compute the signal strength (magnitude of the E field amplitude) at points A and B, as shown in the figure.

$$|\vec{E}| = \frac{\eta_0 k l I_0}{4\pi R} \sin \theta = 60\pi \frac{l}{\lambda} I_0 \left(\frac{\sin \theta}{R} \right) = 5\pi \left(\frac{\sin \theta}{R} \right)$$

$$R_A = 2000 \text{ m}, \quad \theta_A = 90^\circ, \quad |\vec{E}_A| = 5\pi \left(\frac{\sin 90^\circ}{2000} \right) = 7.85 \text{ mV/m}$$

$$R_B = \frac{R_A}{\cos 30^\circ} = \frac{2000}{\cos 30^\circ} = 2309.4 \text{ m}, \quad \theta_B = 60^\circ, \quad |\vec{E}_B| = 5\pi \left(\frac{\sin 60^\circ}{2309.4} \right) = 5.89 \text{ mV/m}$$

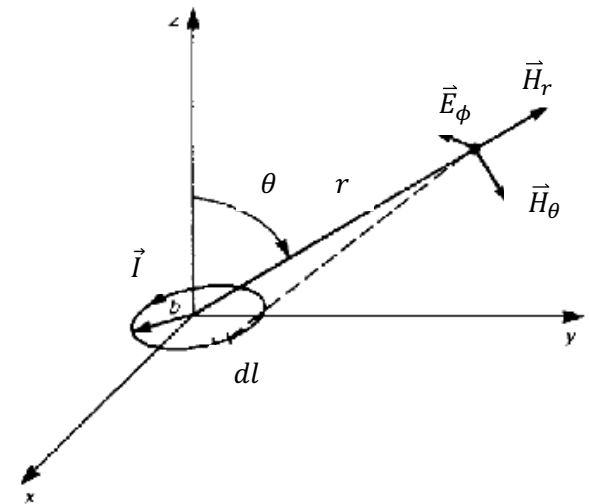


Magnetic Dipole (Loop)

- A dual to the elemental electric dipole is the *elemental magnetic dipole or current loop*. A very small loop of radius b lying in the xy plane carries a phasor current I . It is assumed that the loop circumference is electrically small, i.e., $2\pi b < \lambda_0/10$.
- This loop constitutes a *magnetic dipole moment*

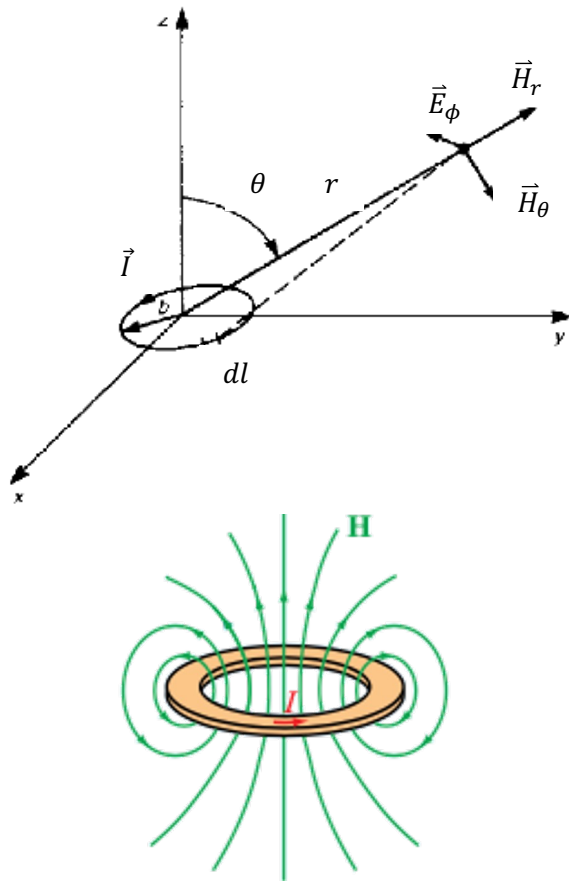
$$\hat{m} = \hat{I} \pi b^2 = IA \quad (\text{in } Am^2)$$

A: Area the loop encloses



Loop antenna is used for measuring **magnetic field emissions** and **immunity testing** at lower frequencies

Magnetic Dipole (Loop)



$$\hat{E}_r = 0$$

$$\hat{E}_\theta = 0$$

$$\hat{E}_\phi = -j \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi} \sin \theta \left(j \frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} \right) e^{-j\beta_0 r}$$

$$\hat{H}_r = j 2 \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi \eta_0} \cos \theta \left(\frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

$$\hat{H}_\theta = j \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi \eta_0} \sin \theta \left(j \frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

$$\hat{H}_\phi = 0$$

k or β : wave number $k = \frac{2\pi}{\lambda}$

Hertzian dipole

$$\tilde{H}_\phi = \frac{I_0 l k^2}{4\pi} e^{-jkR} \left[\frac{j}{kR} + \frac{1}{(kR)^2} \right] \sin \theta,$$

$$\tilde{E}_R = \frac{2I_0 l k^2}{4\pi} \eta_0 e^{-jkR} \left[\frac{1}{(kR)^2} - \frac{j}{(kR)^3} \right] \cos \theta,$$

$$\tilde{E}_\theta = \frac{I_0 l k^2}{4\pi} \eta_0 e^{-jkR} \left[\frac{j}{kR} + \frac{1}{(kR)^2} - \frac{j}{(kR)^3} \right] \sin \theta$$

Magnetic Dipole (Loop)

$$\hat{E}_\phi = -j \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi} \sin \theta \left(j \frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} \right) e^{-j\beta_0 r}$$

$$\hat{H}_r = j 2 \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi \eta_0} \cos \theta \left(\frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

$$\hat{H}_\theta = j \frac{\omega \mu_0 \hat{m} \beta_0^2}{4\pi \eta_0} \sin \theta \left(j \frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j \frac{1}{\beta_0^3 r^3} \right) e^{-j\beta_0 r}$$

Comparing Magnetic Dipole with the fields of the Hertzian dipole, we see that duality exists between the fields of these structures. Observations about the electric (magnetic) field of the electric dipole apply to the magnetic (electric) field of the magnetic dipole.

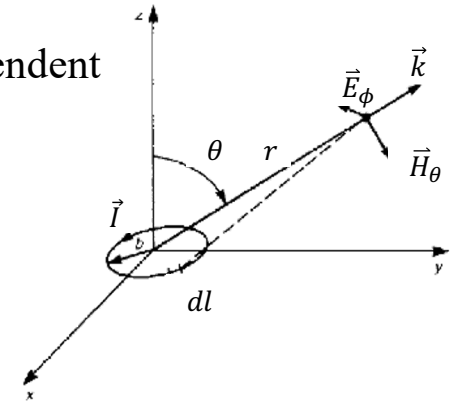


Magnetic Dipole (Loop)

The far field of the magnetic dipole is characterized by the $1/r$ -dependent term:

$$\begin{aligned}\vec{E}_{\text{far field}} &= \frac{\omega\mu_0\hat{m}\beta_0}{4\pi} \sin\theta \frac{e^{-j\beta_0 r}}{r} \hat{\phi} \\ &= \frac{\pi^2 f^2 \mu_0 \hat{I} b^2}{v_0} \sin\theta \frac{e^{-j[2\pi(r/\lambda_0)]}}{r} \hat{\phi}\end{aligned}$$

$$\begin{aligned}\vec{H}_{\text{far field}} &= -\frac{\omega\mu_0\hat{m}\beta_0}{4\pi\eta_0} \sin\theta \frac{e^{-j\beta_0 r}}{r} \hat{\theta} \\ &= \frac{\pi^2 f^2 \mu_0 \hat{I} b^2}{\eta_0 v_0} \sin\theta \frac{e^{-j[2\pi(r/\lambda_0)]}}{r} \hat{\theta}\end{aligned}$$



Magnetic dipole is not an efficient radiator!

Radiation resistance of the magnetic dipole

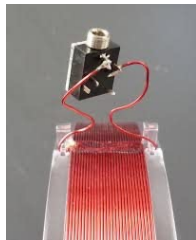
$$R_{\text{rad}} = \frac{P_{\text{av}}}{|\hat{I}_{\text{RMS}}|^2} = 31,170 \left(\frac{A}{\lambda_0^2} \right)^2 \quad A = \pi b^2$$

Consider a loop of radius 1 cm. At 300 MHz the radiation resistance is $3.08 \text{ m}\Omega$. In order to radiate 1 W, the loop requires a (RMS) current of 18 A. At 3 MHz the radiation resistance is $3.08 \times 10^{-11} \Omega$, and the (RMS) current required to radiate 1 W is $1.8 \times 10^5 \text{ A}$!



Small loop antenna:

- The small loop antenna is very popular in receiving antenna.
- Multi-turn small loops are popular in AM broadcast receiver.
- Small loop antennas are also used in direction-finding receivers and for EMI field strength probes.



7.3 Antenna Parameters: power pattern

Total Radiated Power P_{rad}

Differential power radiated through dA

$$dP_{\text{rad}} = \mathbf{S}_{\text{av}} \cdot d\mathbf{A} = \mathbf{S}_{\text{av}} \cdot \hat{\mathbf{R}} dA = S dA$$

Differential area

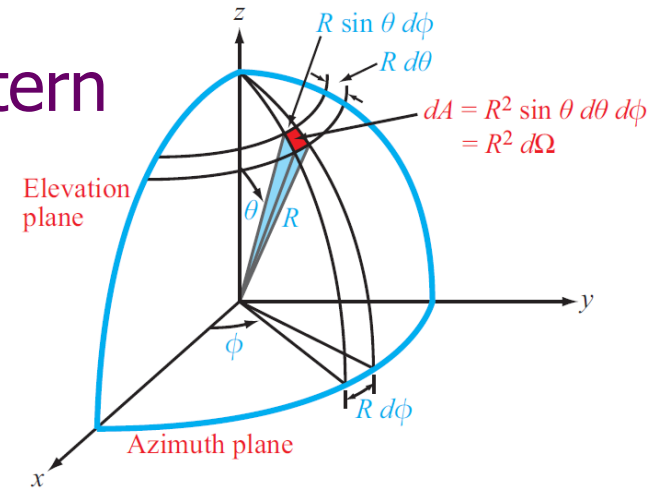
$$dA = R^2 \sin \theta \, d\theta \, d\phi$$

Solid Angle

$$d\Omega = \frac{dA}{R^2} = \sin \theta \, d\theta \, d\phi$$

Power radiated through dA

$$dP_{\text{rad}} = R^2 S(R, \theta, \phi) \, d\Omega$$

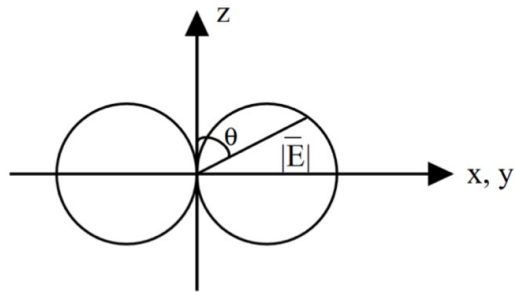


Definition of solid angle $d\Omega = \sin \theta \, d\theta \, d\phi$.

$$\begin{aligned} P_{\text{rad}} &= R^2 \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} S(R, \theta, \phi) \sin \theta \, d\theta \, d\phi \\ &= R^2 S_{\text{max}} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} F(\theta, \phi) \sin \theta \, d\theta \, d\phi \\ &= R^2 S_{\text{max}} \iint_{4\pi} F(\theta, \phi) \, d\Omega \quad (\text{W}), \end{aligned}$$

Total Radiated Power

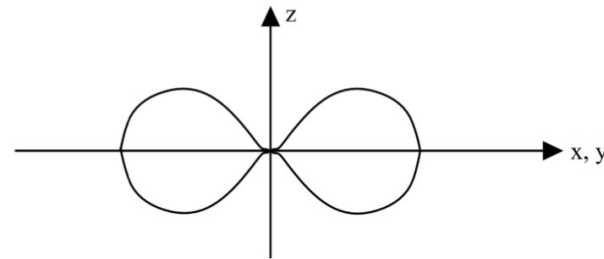
Antenna Parameters: field pattern



Radiation **field pattern** of a Hertzian dipole or small loop antenna.

$$\frac{E_{\theta}}{E_{\theta, \max}} = \sin \theta$$

The field pattern with its maximum value is 1



Radiation **power pattern** of a Hertzian dipole or small loop antenna.

$$F(\theta, \phi) = \sin^2 \theta \quad \text{For power pattern}$$

Example of 3-D Pattern

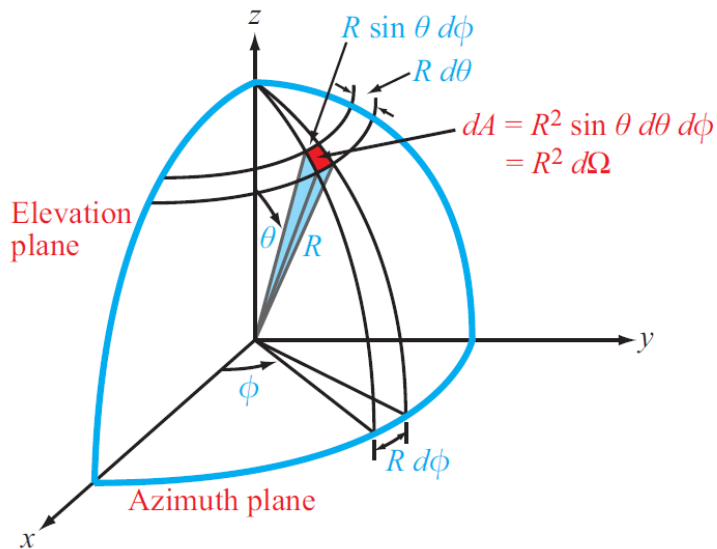
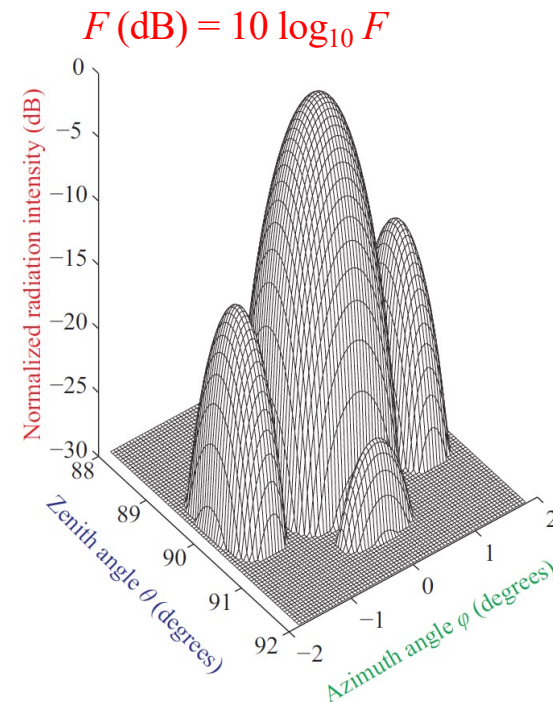


Figure 9-8: Definition of solid angle $d\Omega = \sin \theta d\theta d\phi$.

Principal planes:

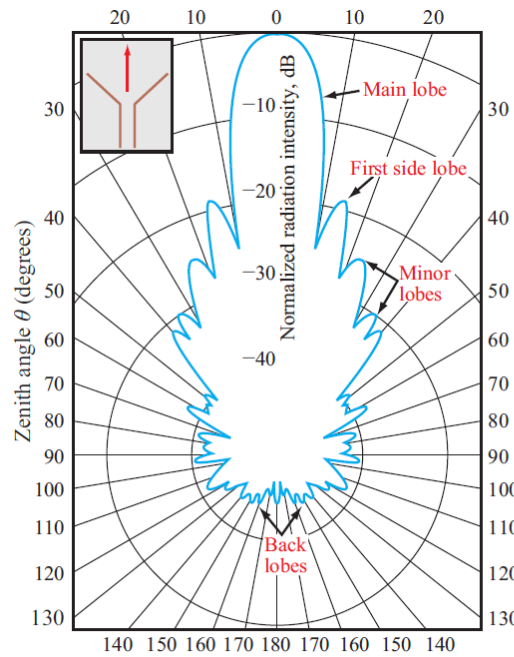
1. **Elevation plane** (x-z and y-z planes, etc.)
2. **Azimuth plane** (x-y plane)

normalized radiation intensity $F(\theta, \phi)$

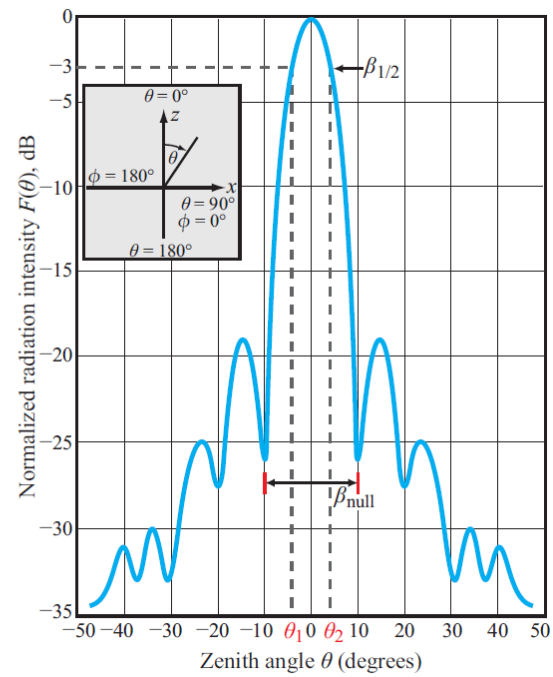


9-9: Three-dimensional pattern of a narrow-beam antenna.

Polar and Rectangular Plots



(a) Polar diagram



(b) Rectangular plot

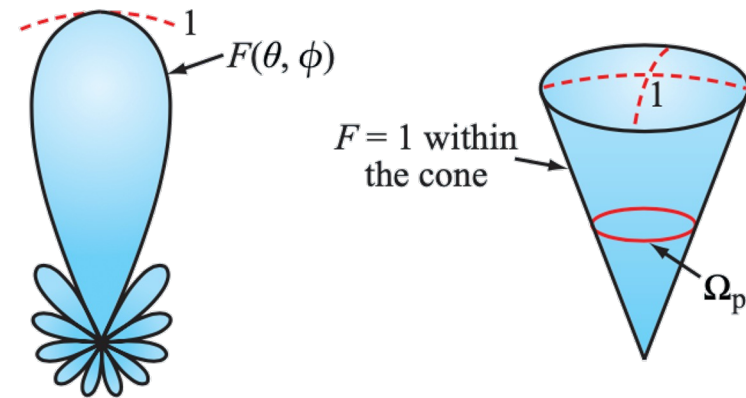
Beam Dimensions

1. Pattern solid angle

$$\Omega_p = \iint_{4\pi} F(\theta, \phi) d\Omega \quad (\text{sr}).$$

the equivalent width of the main lobe

For an isotropic antenna with $F(\theta, \phi) = 1$ in all directions, $\Omega_p = 4\pi$ (sr).



(a) Actual pattern

(b) Equivalent solid angle

The pattern solid angle Ω_p defines an equivalent cone over which all the radiation of the actual antenna is concentrated with uniform intensity equal to the maximum of the actual pattern.

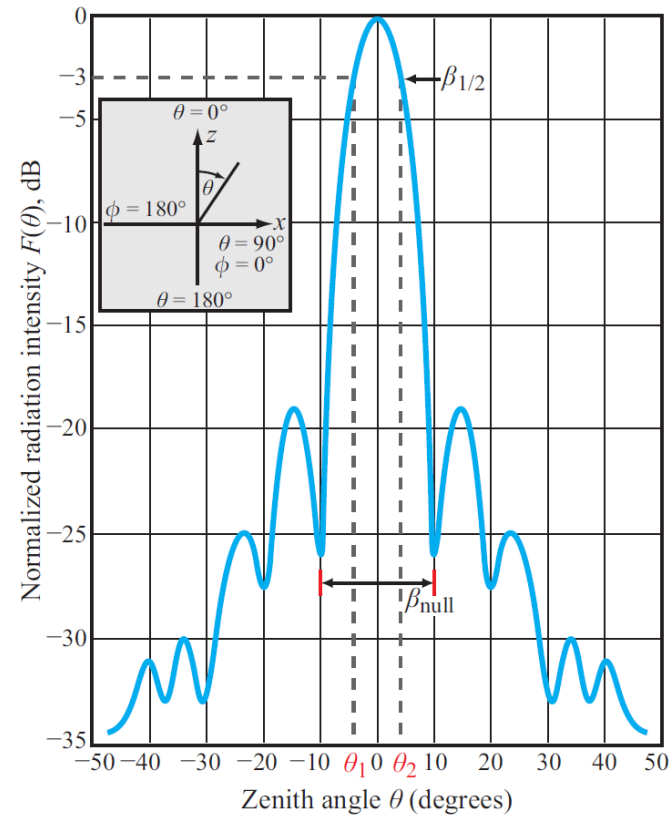
Beam Dimensions

2. Half-power beamwidth

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

where θ_1 and θ_2 are the **half-power angles** at which $F(\theta, 0) = 0.5$

Since 0.5 corresponds to -3 dB, the half power beamwidth is also called the 3-dB beamwidth.



For the Hertzian dipole antenna pattern, $F(\theta) = \sin^2 \theta$.

is maximum at $\theta = 90^\circ$, θ_2 is at 135° , and θ_1 is at 45° . So, $\beta = 135^\circ - 45^\circ = 90^\circ$.

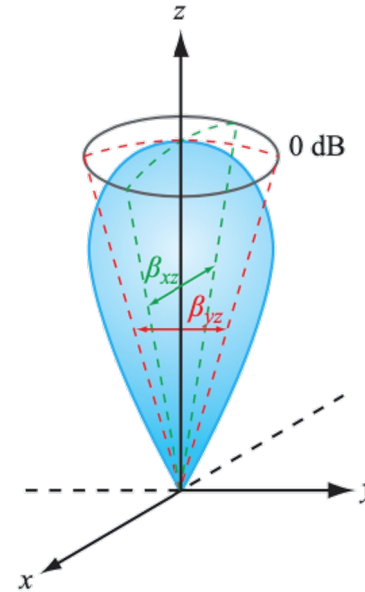
Beam Dimensions

1. Pattern solid angle

$$\Omega_p = \iint_{4\pi} F(\theta, \phi) d\Omega \quad (\text{sr}).$$

the equivalent width of the main lobe

$$\Omega_p \approx \beta_{xz}\beta_{yz}$$



The solid angle of a radiation pattern is approximately equal to the product of the half-power beamwidths in the two principal planes $\Omega_p \approx \beta_{xz}\beta_{yz}$.

Antenna Parameters: Directivity

Directivity

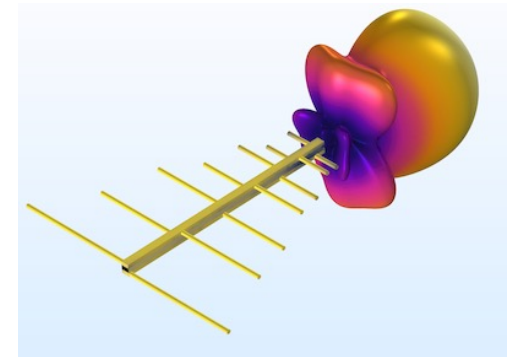
$$D = \frac{F_{\max}}{F_{\text{av}}}$$

$$F(\theta, \phi) = \frac{S(R, \theta, \phi)}{S_{\max}}$$

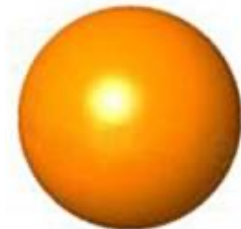
$$= \frac{1}{\frac{1}{4\pi} \iint_{4\pi} F(\theta, \phi) d\Omega}$$

$$= \frac{4\pi}{\Omega_p} \quad (\text{dimensionless})$$

The narrower Ω_p of an antenna pattern is, the greater is the directivity.
For an isotropic antenna, $\Omega_p = 4\pi$; hence, its directivity $D_{iso} = 1$.



Antenna pattern of log-periodic antenna



Antenna pattern of isotropic antenna

Antenna Parameters: Directivity

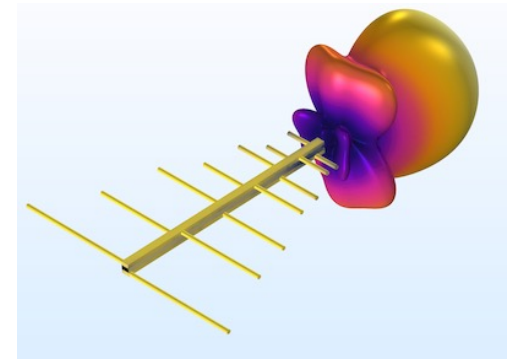
Directivity

$$D = 4\pi/\Omega_p$$

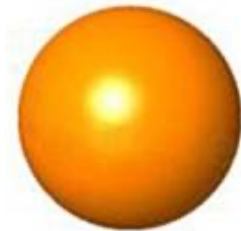
$$\Omega_p = \iint_{4\pi} F(\theta, \phi) d\Omega \quad (\text{sr}).$$

$$P_{rad} = R^2 S_{max} \iint_{4\pi} F(\theta, \phi) d\Omega = R^2 S_{max} \Omega_p$$

$$\Rightarrow D = \frac{4\pi R^2 S_{max}}{P_{rad}} \quad \text{and} \quad P_{rad} = \frac{4\pi R^2 S_{max}}{D}$$



Antenna pattern of log-periodic antenna



Antenna pattern of isotropic antenna

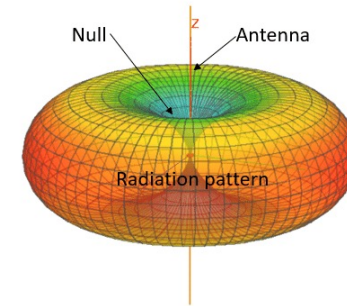
Antenna Parameters: Directivity

Directivity of Hertzian dipole

$$F(\theta) = \sin^2 \theta$$

$$D = \frac{4\pi}{\iint_{4\pi} F(\theta, \phi) \sin \theta \, d\theta \, d\phi}$$
$$= \frac{4\pi}{\int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \sin^3 \theta \, d\theta \, d\phi} = \frac{4\pi}{8\pi/3} = 1.5$$

or, equivalently, 1.76 dB.



Radiation pattern of Hertzian dipole

Antenna Parameters: efficiency and gain

Radiation efficiency:

$$\xi = \frac{P_{\text{rad}}}{P_t} \quad (\text{dimensionless}). \quad (0 \leq \xi \leq 1) \quad P_t: \text{total transmitter power}$$

Gain: 4π times the ratio of radiation intensity in a given direction to the **total transmitter power of the antenna** from the connected transmitter

$$G = \frac{4\pi R^2 S_{\text{max}}}{P_t}$$



$$D = \frac{4\pi}{\Omega_p} = \frac{4\pi R^2 S_{\text{max}}}{P_{\text{rad}}}$$

- If all input power appeared as radiated power ($P_t = P_{\text{rad}}$), Directivity = Gain.
- In reality, some of the power is lost in the antenna absorbed by the antenna and nearby structures).

$$G = \xi D$$



Antenna Parameters: Loss Resistances , radiation efficiency

- Input impedance

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

R_{in} : Dissipation = Radiation + Ohmic loss $R_{in} = R_{rad} + R_{loss}$

X_{in} : Power stored near the antenna

$$P_t = P_{rad} + P_{loss} = \frac{1}{2}I_0^2 R_{rad} + \frac{1}{2}I_0^2 R_{loss}$$

R_{rad} : radiation resistance

R_{loss} : loss resistance

- Radiation Efficiency

$$\xi = \frac{P_{rad}}{P_t} = \frac{P_{rad}}{P_{rad} + P_{loss}} = \frac{R_{rad}}{R_{rad} + R_{loss}}$$



Example: Radiation resistance and efficiency of a Hertzian Dipole

A 4-cm-long center-fed dipole is used as an antenna at 75 MHz. The antenna wire is made of copper and has a radius $a = 0.4\text{mm}$. The loss resistance of a circular wire of length l is given by

$$R_{loss} = \frac{l}{\sigma A} = \frac{l}{\sigma 2\pi a \delta} = \frac{l}{2\pi a} \sqrt{\frac{\pi f \mu_c}{\sigma_c}}$$

Where μ_c and σ_c are the magnetic permeability and conductivity of the wire. Calculate the radiation resistance and the radiation efficiency of the dipole antenna.

Solution: a) At 75 MHz $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{7.5 \times 10^7} = 4\text{m}$

The length to wavelength ratio is $l / \lambda = 4\text{cm} / 4\text{m} = 0.01$, so it is a short dipole.

For Hertzian dipole,

$$P_{\text{rad}} = 40\pi^2 I_0^2 \left(\frac{l}{\lambda} \right)^2$$



Example: Radiation resistance and efficiency of a Hertzian Dipole

$$P_{\text{rad}} = 40\pi^2 I_0^2 \left(\frac{l}{\lambda}\right)^2$$

$$P_{\text{rad}} = \frac{1}{2} I_0^2 R_{\text{rad}} \implies R_{\text{rad}} = 80\pi^2 (l/\lambda)^2 \quad (\Omega)$$

$$\text{For } l/\lambda = 4\text{cm} / 4\text{m} = 0.01 \implies R_{\text{rad}} = 0.08 \, \Omega \quad \text{radiation resistance}$$

b) Next, we determine the loss resistance R_{loss} and radiation efficiency.

$$\text{For copper, } \mu_c \approx \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \quad \sigma = 5.8 \times 10^7 \text{ S/m}$$

$$R_{\text{loss}} = \frac{l}{2\pi a} \sqrt{\frac{\pi f \mu_c}{\sigma_c}} = \frac{4 \times 10^{-2}}{2\pi \times 4 \times 10^{-4}} \left(\frac{\pi \times 75 \times 10^6 \times 4\pi \times 10^{-7}}{5.8 \times 10^7} \right)^{1/2} = 0.036 \, \Omega$$

Therefore, the radiation efficiency is

$$\xi = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}} = \frac{0.08}{0.08 + 0.036} = 0.69$$

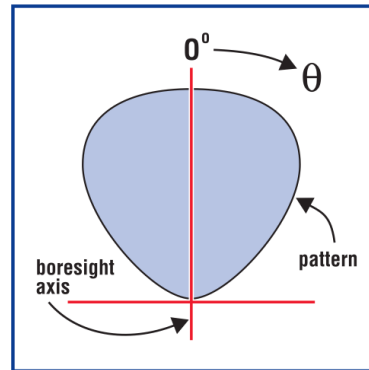
The dipole is 69% efficient.



Basic Antenna Terms Used in EMC Measurement

Antenna Pattern

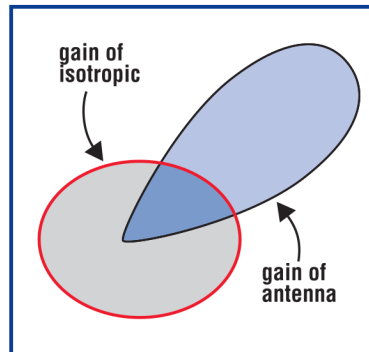
The pattern shows the response of the antenna as the viewing angle is varied.



Gain

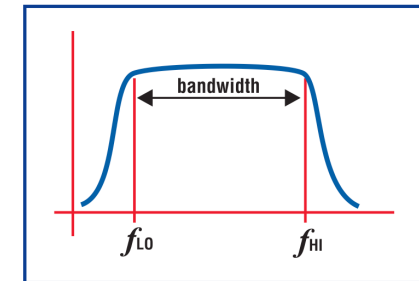
Gain is a key performance parameter which combines the antenna's directivity and radiation efficiency.

$$G = \xi D$$



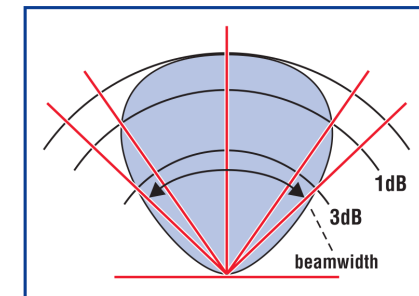
Bandwidth

The bandwidth of an antenna is the operating frequency range of the antenna



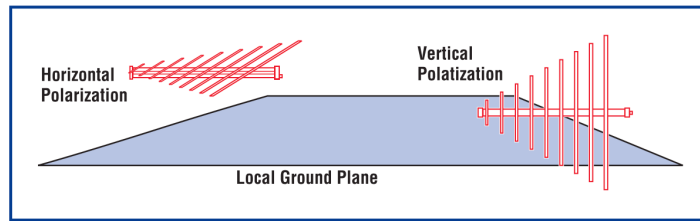
Beamwidth

the viewing angle of the antenna, in the plane of measurement, when power has fallen by 3dB - HPBW



Basic Antenna Terms Used in EMC Measurement (cont.)

Polarization



VSWR

$$VSWR = \frac{V_{max}}{V_{min}}$$

low VSWR is better.

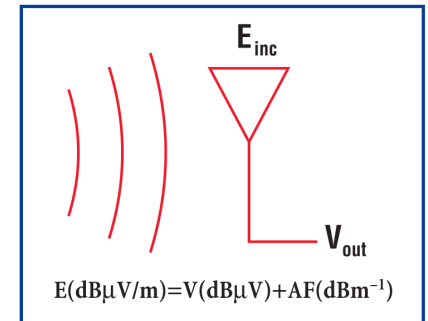
High VSWR means return power is high.

Antenna Factor

This is the parameter of an EMC antenna that is used in the calculations of field strength during radiated emissions measurement.

$$AF = \frac{E}{V}$$

Convert between the **E-field** and the **voltage** measured at the output of an antenna.



4 Dipole and Monopole

Half-wave dipole

1. Current in half-wave dipole

$$i(t) = I_0 \cos \omega t \cos kz = \Re \left[I_0 \cos kz e^{j\omega t} \right]$$

whose phasor is

$$\tilde{I}(z) = I_0 \cos kz, \quad -\lambda/4 \leq z \leq \lambda/4$$

2. For Hertzian dipole of length l , E field is:

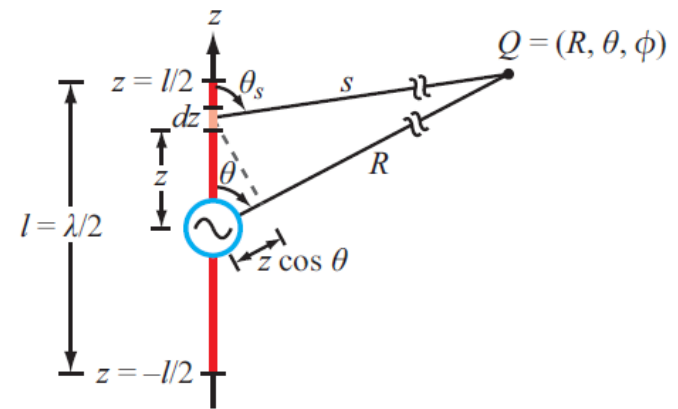
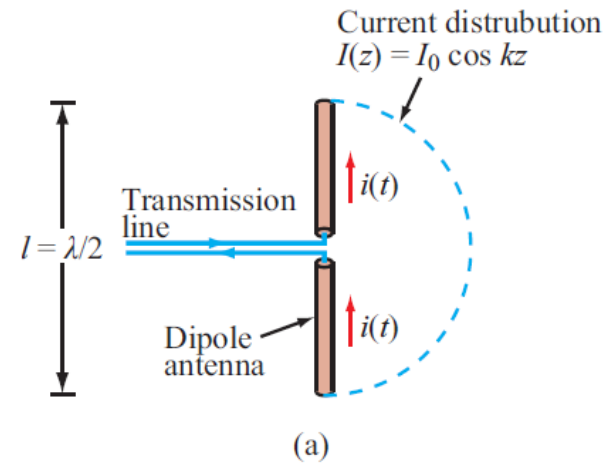
$$\tilde{E}_\theta = \frac{j I_0 l k \eta_0}{4\pi} \left(\frac{e^{-jkR}}{R} \right) \sin \theta \quad (\text{V/m})$$

3. Each length element dz of half-wave dipole is like a Hertzian dipole, radiating a field

$$d\tilde{E}_\theta(z) = \frac{jk\eta_0}{4\pi} \tilde{I}(z) dz \left(\frac{e^{-jks}}{s} \right) \sin \theta_s$$

4. For the entire dipole, the total radiated field is

$$\tilde{E}_\theta = \int_{z=-\lambda/4}^{\lambda/4} d\tilde{E}_\theta$$



(b)
Center-fed half-wave dipole

Half-Wave Dipole (cont.)

Parallel-ray approximation

$$\begin{cases} s \approx R - z \cos \theta \\ \theta_s \approx \theta \end{cases} \quad \Rightarrow \quad \tilde{E}(\theta) = \frac{jk\eta_0}{4\pi} \tilde{I}(z) dz \left(\frac{e^{-jkR}}{R} \right) \sin \theta e^{jkz \cos \theta}$$

Integration leads to:

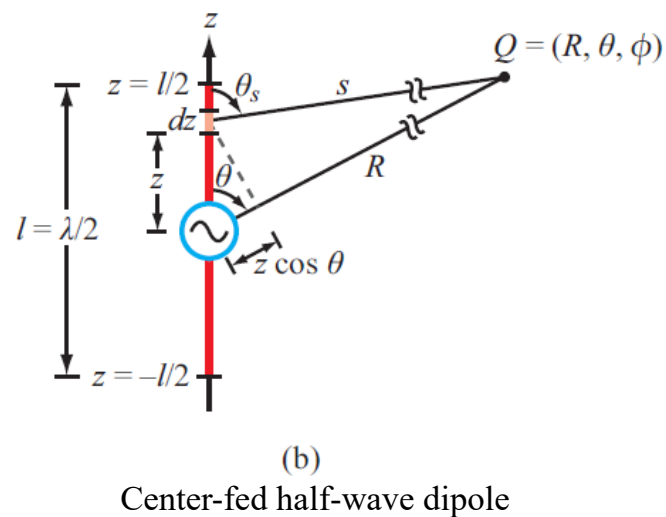
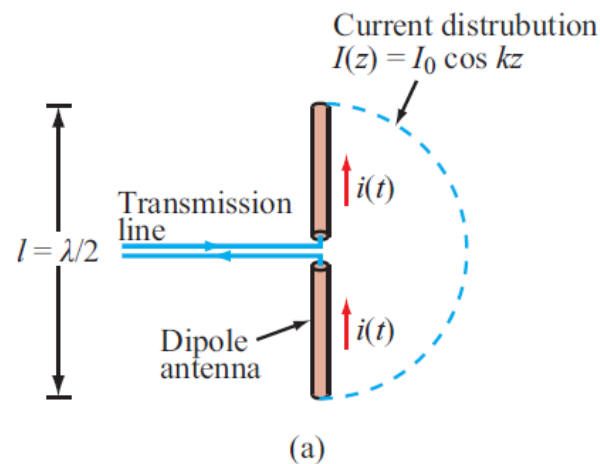
$$\begin{aligned}\tilde{E}_\theta &= j60I_0 \left\{ \frac{\cos[(\pi/2)\cos\theta]}{\sin\theta} \right\} \left(\frac{e^{-jkR}}{R} \right), \\ \tilde{H}_\phi &= \frac{\tilde{E}_\theta}{\eta_0}.\end{aligned}$$

time-average power density

$$\begin{aligned} S(R, \theta) &= \frac{|\tilde{E}_\theta|^2}{2\eta_0} \\ &= \frac{15I_0^2}{\pi R^2} \left\{ \frac{\cos^2[(\pi/2) \cos \theta]}{\sin^2 \theta} \right\} \\ &= S_0 \left\{ \frac{\cos^2[(\pi/2) \cos \theta]}{\sin^2 \theta} \right\} \end{aligned}$$

normalized radiation intensity

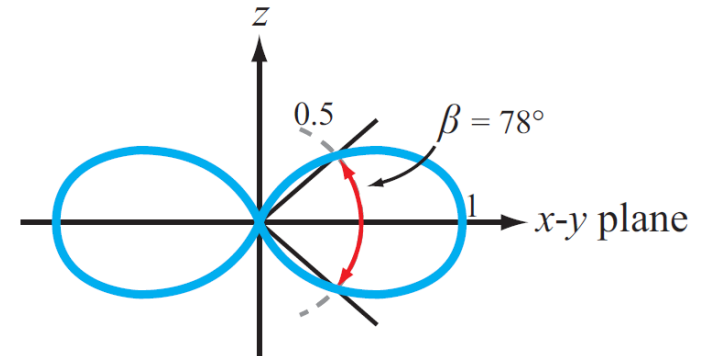
$$F(\theta) = \frac{S(R, \theta)}{S_0} = \left\{ \frac{\cos[(\pi/2) \cos \theta]}{\sin \theta} \right\}^2$$



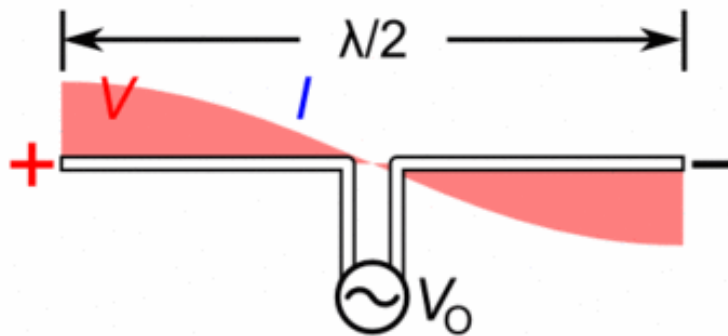
Radiation Pattern of Half-Wave Dipole

$$F(\theta) = \frac{S(R, \theta)}{S_0} = \left\{ \frac{\cos[(\pi/2) \cos \theta]}{\sin \theta} \right\}^2$$

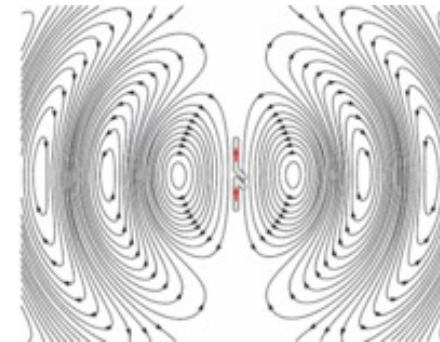
Radiation pattern resembles that of the Hertzian dipole. Its beamwidth is slightly narrower, 78 degrees compared with 90 degrees for the Hertzian dipole.



(a) $l = \lambda/2$



Sinusoidal standing waves of voltage and current



electric fields

Other Half-Wave Dipole Properties

1. Directivity

$$\begin{aligned} P_{\text{rad}} &= R^2 \iint_{4\pi} S(R, \theta) d\Omega \\ &= \frac{15I_0^2}{\pi} \int_0^{2\pi} \int_0^\pi \left\{ \frac{\cos[(\pi/2) \cos \theta]}{\sin \theta} \right\}^2 \sin \theta d\theta d\phi \end{aligned}$$

Numerical integration gives: $P_{\text{rad}} = 36.6 I_0^2$

$$D = \frac{4\pi R^2 S_{\text{max}}}{P_{\text{rad}}} = \frac{4\pi R^2}{36.6 I_0^2} \left(\frac{15 I_0^2}{\pi R^2} \right) = 1.64,$$

or, equivalently, 2.15 dB.

Its directivity is slightly larger (1.64 compared with 1.5 for the short dipole)

2. Radiation Resistance

$$R_{\text{rad}} = \frac{2P_{\text{rad}}}{I_0^2} = \frac{2 \times 36.6 I_0^2}{I_0^2} \simeq 73 \Omega$$

its radiation resistance is 73Ω , which is orders of magnitude larger than that of a short dipole.

The input impedance is

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

X_{in} is a strong function of l/λ , and that it decreases from 42Ω at $l/\lambda = 0.5$ to zero at $l/\lambda = 0.48$

- Z_{in} becomes purely real and equal to 73Ω
- match the dipole to a 75Ω transmission line

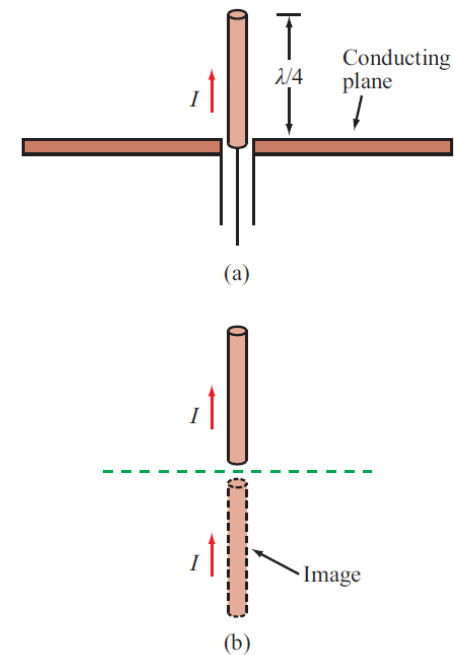


Quarter-Wave Monopole

When placed over a conducting ground plane, a **quarter-wave monopole** antenna excited by a source at its base exhibits the same radiation pattern in the region above the ground plane as a **half-wave dipole** in free space.

However, its radiation resistance is only half of that of a half-wave dipole, namely 36.5Ω .

$\lambda/4$ monopole	$\lambda/2$ dipole
Same E field in far field region, normalized radiation intensity $F(\theta, \phi)$ (in upper half-space)	
$P_{rad} = 18.3I_0^2$ $R_{rad} = 36.5\Omega$	$P_{rad} = 36.6I_0^2$ $R_{rad} = 73\Omega$

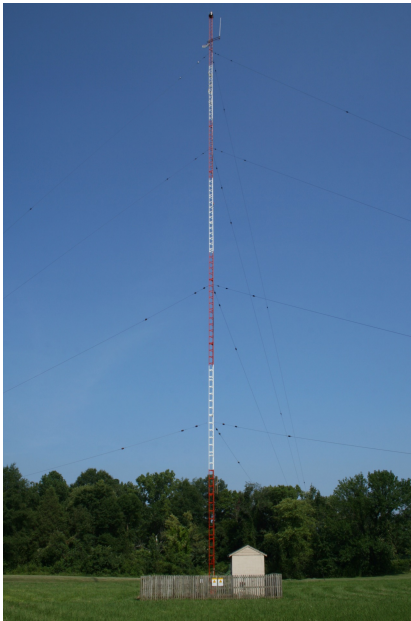


A quarter-wave monopole above a conducting plane is equivalent to a full half-wave dipole in free space (Image theory)



Poll

What is the physical length of the antenna operating at
(a) 1 MHz (in the AM broadcast band), using a quarter-wave monopole
(b) 100 MHz (FM broadcast band), using a half-wave dipole



AM radio station in North Carolina



FM Antenna



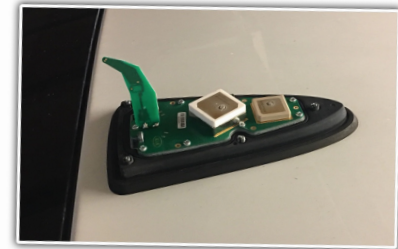
Quarter-Wave Monopole Application



Whip antenna on old model vehicle



Shark fin antenna on Roof

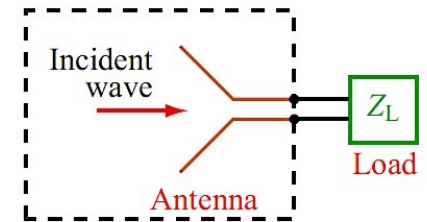


Inside side mirrors



On the rear window

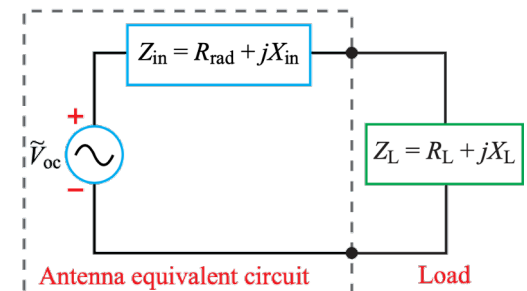
Antenna Parameters: effective aperture



(a) Receiving antenna

The **effective aperture** of an antenna, A_e , is the ratio of power received in its load impedance, P_R , to the power density of the incident wave, S_{av} , when the polarization of the incident wave and the polarization of receiving antenna are matched:

$$A_e = \frac{P_R}{S_{av}} \quad (in \ m^2)$$



(b) Equivalent circuit

The maximum effective aperture A_{em} is the A_e when the maximum transferring to the load takes place.

Example

Compute the A_{em} (maximum effective aperture) of a Hertzian dipole antenna.

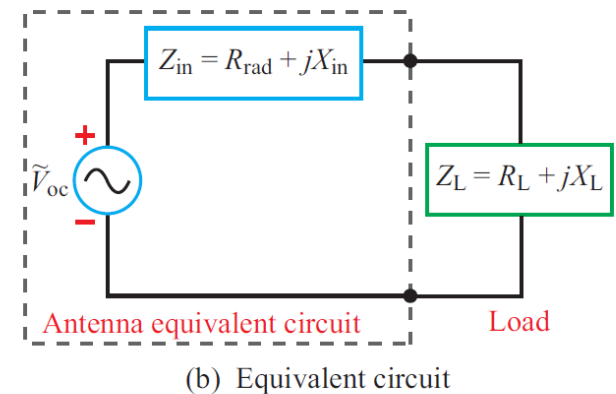
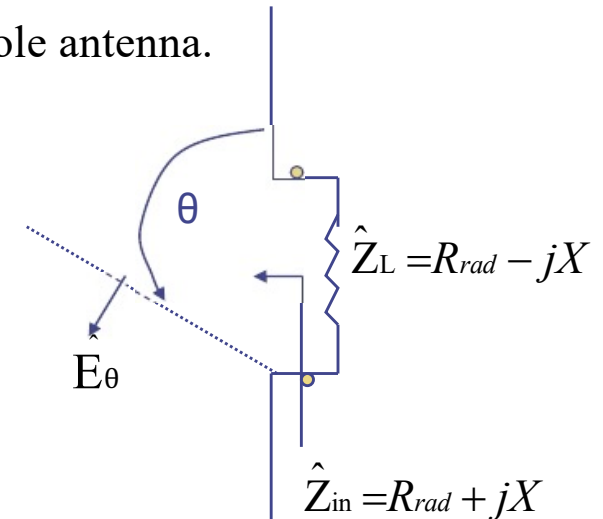
Solution: To solve A_{em} , two conditions should be kept in mind:

- (1) matched polarization for the incident wave and the antenna.
- (2) matched load. (ie. $Z_L = Z_{in}^*$)

Suppose the incident wave is arriving at an angle θ

(1) the open-circuit voltage produced at the terminals of the antenna is

$$|V_{oc}| = |\hat{E}_\theta| dl \sin \theta$$



(2) power density in the incident wave

$$S_{av} = \frac{1}{2} \frac{|E_\theta|^2}{\eta_0}$$

(3) the load is matched

the received power $\left(\frac{1}{2} I^2 R = \frac{1}{2} \left(\frac{V_{oc}}{2R_{rad}} \right)^2 R_{rad} \right)$

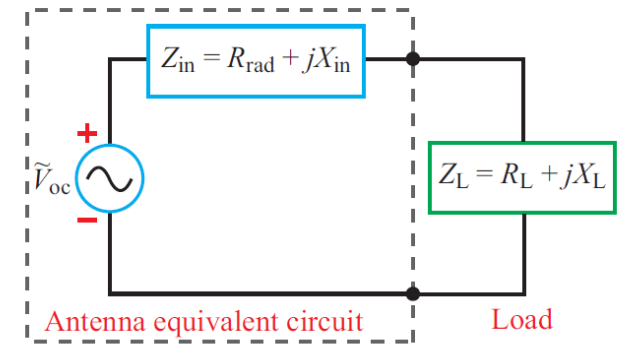
$$P_R = \frac{|V_{oc}|^2}{8R_{rad}} = \frac{|E_\theta|^2 dl^2 \sin^2 \theta}{8R_{rad}}$$

(4) radiation resistance for Hertzian dipole

$$R_{rad} = 80\pi^2 \left(\frac{dl}{\lambda_0} \right)^2$$

$$P_R = \frac{|E_\theta|^2 \lambda^2}{640\pi^2} \sin^2 \theta$$

$$(5) A_{em}(\theta, \phi) = \frac{P_R}{S_{av}} = 1.5 \sin^2 \theta \left(\frac{\lambda_0^2}{4\pi} \right) = \frac{\lambda_0^2}{4\pi} D(\theta, \phi)$$



(b) Equivalent circuit

Matched load $Z_L = Z_{in}^*$

d. For general antennas, the above relation hold.

$$D(\theta, \phi) = \frac{4\pi}{\lambda_0^2} A_{em}(\theta, \phi) \quad \text{for lossless antenna.}$$

$$G(\theta, \phi) = \frac{4\pi}{\lambda_0^2} A_{em}(\theta, \phi) \quad \text{for lossy antenna.}$$

The maximum effective aperture of an antenna used for reception is related to the gain in the direction of the incoming wave of that antenna when it is used for transmission.

Example

The effective area of an antenna is 9 m^2 . What is its directivity in decibels at 3 GHz?

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{3 \times 10^9} = 0.1 \text{ m}$$

$$\text{From } A_{em}(\theta, \phi) = \frac{\lambda^2}{4\pi} D(\theta, \phi)$$

$$\rightarrow D(\theta, \phi) = \frac{4\pi}{\lambda^2} A_{em}(\theta, \phi) = \frac{4\pi}{0.1^2} \cdot 9 = 3600\pi$$

$$D \Big|_{dB} = 10 \log_{10} 3600\pi = 40.53 \text{ dB}$$



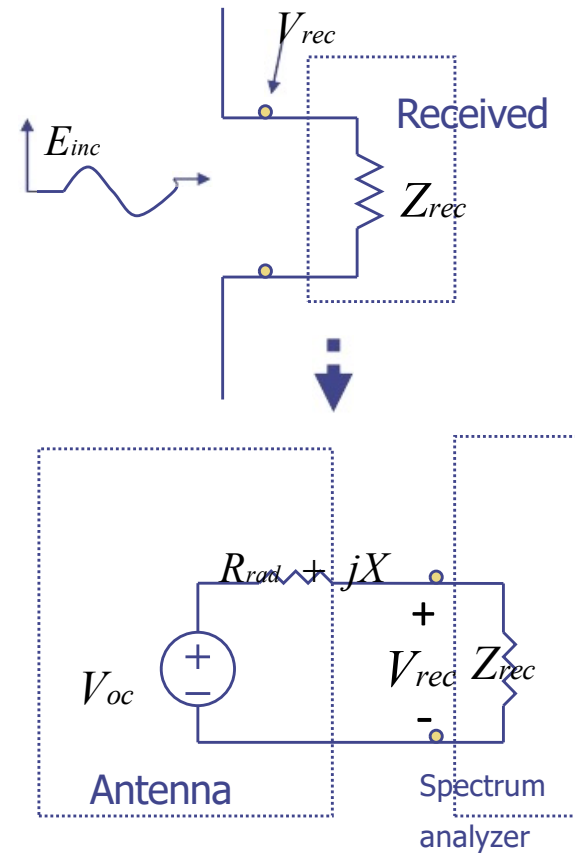
Antenna Factor

Antenna factor is a common way to characterize the reception properties of EMC antenna.

Antenna factor is defined as the ratio of the incident electric field at the surface of the measurement antenna to the received voltage at the antenna terminals:

$$AF = \frac{|E_{inc}|}{|V_{rec}|} \quad (1/m)$$

$$AF_{dBm^{-1}} = E_{dBV/m} - V_{dBV} = E_{dB\mu V/m} - V_{dB\mu V}$$



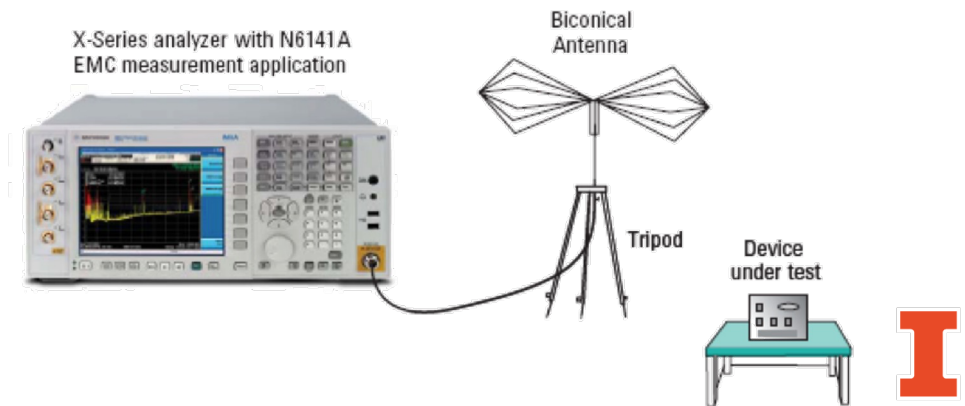
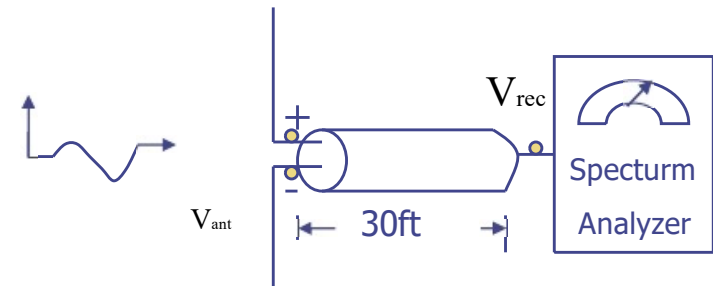
Example: Find the antenna factor at 100 MHz for following measurement data.

- (1) The field intensity of antenna surface is $60 \text{ dB}\mu\text{V}/\text{m}$
- (2) The Spectrum Analyzer measures $40 \text{ dB}\mu\text{V}$
- (3) Coaxial loss = $4.5 \text{ dB}/100\text{ft}$

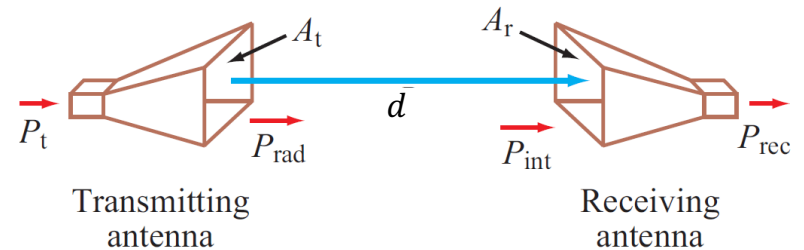
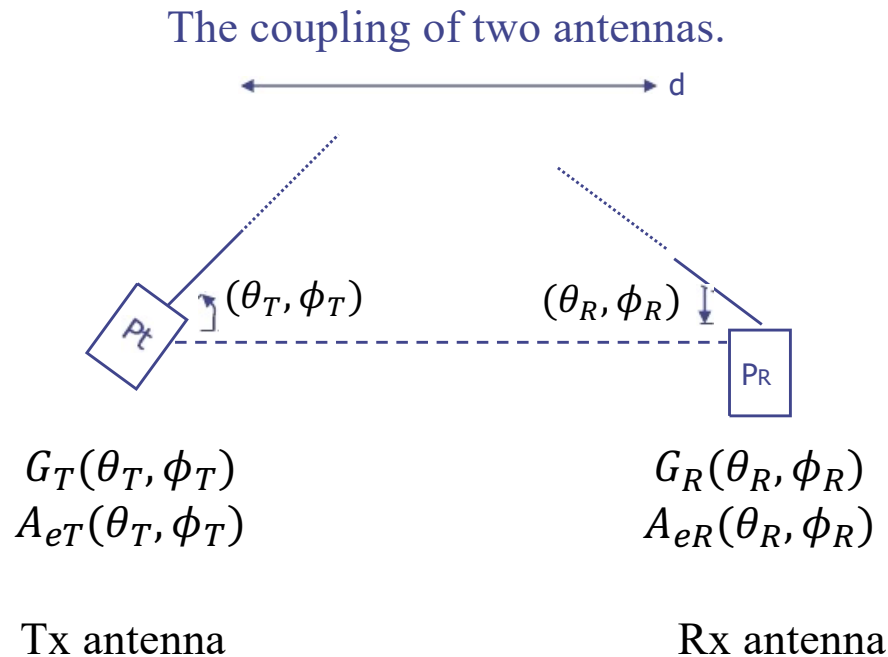
solution:

$$E (\text{dB}\mu\text{V}/\text{m}) = AF (\text{dBm}^{-1}) + V_{SA} (\text{dB}\mu\text{V}) + \text{cable loss (dB)}$$

$$AF_{\text{dBm}^{-1}} = 60 \frac{\text{dB}\mu\text{V}}{\text{m}} - \left(40 \text{ dB}\mu\text{V} + 4.5 \times \frac{30}{100} \text{ dB} \right) = 18.65 \text{ dBm}^{-1}$$



The Friis transmission equation



So far, we discussed

- transmitting antenna parameters
 - radiation pattern, normalized field intensity, directivity, efficiency, gain
- receiving antenna parameters
 - effective aperture, and antenna factor

Friis transmission equation

(1) The power density at the receiving antenna of distance d .

$$S_{av} = \frac{P_T}{4\pi d^2} G_T(\theta_T, \phi_T)$$

(2) and by the definition of effective aperture, the received power P_R

$$P_R = S_{av} A_{eR}(\theta_R, \phi_R)$$

$$\frac{P_R}{P_T} = \frac{G_T(\theta_T, \phi_T) A_{eR}(\theta_R, \phi_R)}{4\pi d^2}$$

(3) and we know

$$G_R(\theta_R, \phi_R) = \frac{4\pi}{\lambda^2} A_{eR}(\theta_R, \phi_R)$$

$$\frac{P_R}{P_T} = G_T(\theta_T, \phi_T) G_R(\theta_R, \phi_R) \left(\frac{\lambda_0}{4\pi d} \right)^2$$

Friis transmission formula

(4) In terms of dB

$$10 \log_{10} \left(\frac{P_R}{P_T} \right) = G_{T,dB} + G_{R,dB} - 20 \log_{10} f - 20 \log_{10} d + 147.6$$



Friis transmission equation

Note:

Friss transmission equation is valid under two assumptions:

- (1) the receiving antenna must be matched to its load impedance and the polarization of the incoming wave.
- (2) two antenna should be in the far field

i.e. $d > 2D^2/\lambda$

$$d \gg D$$

D is the maximum dimension of the antenna



Example

A 3 GHz microwave link consists of two identical antennas each with a gain of 30 dB. Determine the received power, given that the transmitter output power is 1 kW and the two antennas are 10 km apart.

$$\frac{P_R}{P_T} = G_T(\theta_T, \phi_T) G_R(\theta_R, \phi_R) \left(\frac{\lambda_0}{4\pi d} \right)^2 \quad \text{Friis transmission formula}$$

$$G = 10^{\left(\frac{30}{10}\right)} = 1000$$

$$P_R = 10^3 \times 10^3 \times 10^3 \times \left(\frac{3 \times 10^8}{3 \times 10^9 \times 4\pi \times 10^4} \right)^2 = \frac{1}{160\pi^2} = 0.633 \text{ mW}$$



5 Broadband Measurement Antennas

- FCC prefers to use half-wave dipoles for measurement of radiated emission from 30MHz~1GH, it is time consuming because its length must be physically adjusted to provide $\lambda/2$ at each frequency.
- Broadband measurement antennas for EMC.
 - 1.Input / output impedance is fairly constant over the frequency band.
 - 2.The pattern is fairly constant over the frequency band.
- Two commonly used antenna
 - 1.biconical antenna -- 30MHz~200MHz
 - 2.log-periodic antenna -- 200MHz~1GHz



5 Broadband Measurement Antennas

**Cartoontronics
Inc.**

"SPECIAL" ANTENNAS FOR EMC! by Arturo Mediano

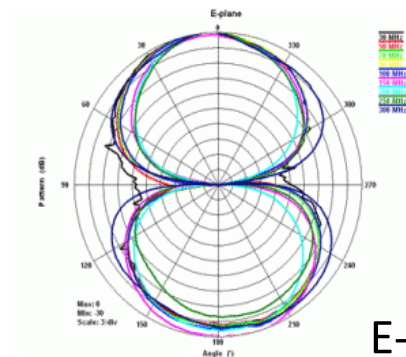


The Biconical Antenna

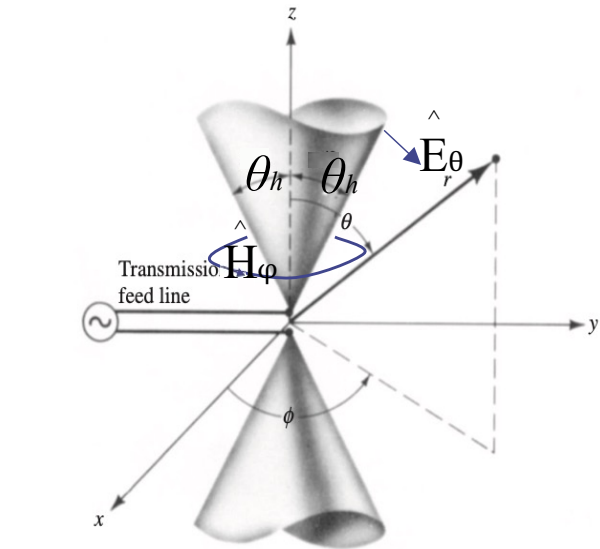
- ✧ Infinite biconical antenna
 1. half angle θ_h .
 2. feed point with small gap.
- ✧ In the free space, the symmetry

Suggests:

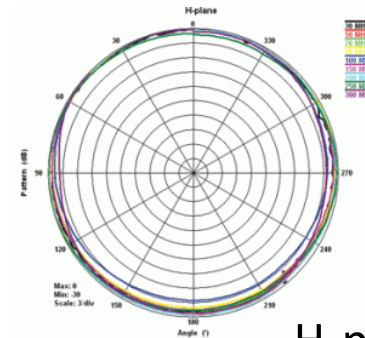
$$\hat{E}_\theta = \eta_0 \hat{H}_\phi = \eta_0 \frac{H_0}{\sin \theta} \frac{e^{-j\beta_0 r}}{r}$$



E-plane



$$\hat{H}_\phi = \frac{H_0}{\sin \theta} \frac{e^{-j\beta_0 r}}{r}$$



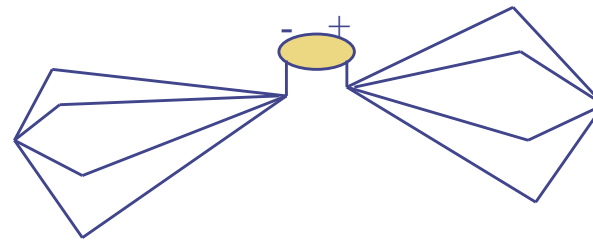
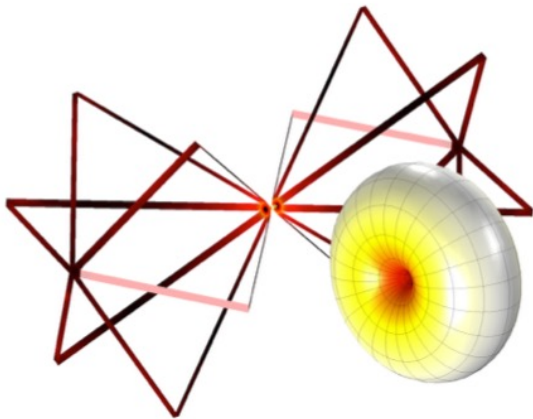
H-plane

The Biconical Antenna (Cont.)

note: (1) $\hat{Z}_{in}$ is independent of frequency(flat response) for infinite core
(2) but practice antenna is finite length, so

$$\hat{Z}_{in} = R + jX \rightarrow \text{storage energy will appear}$$

EMC biconical antenna



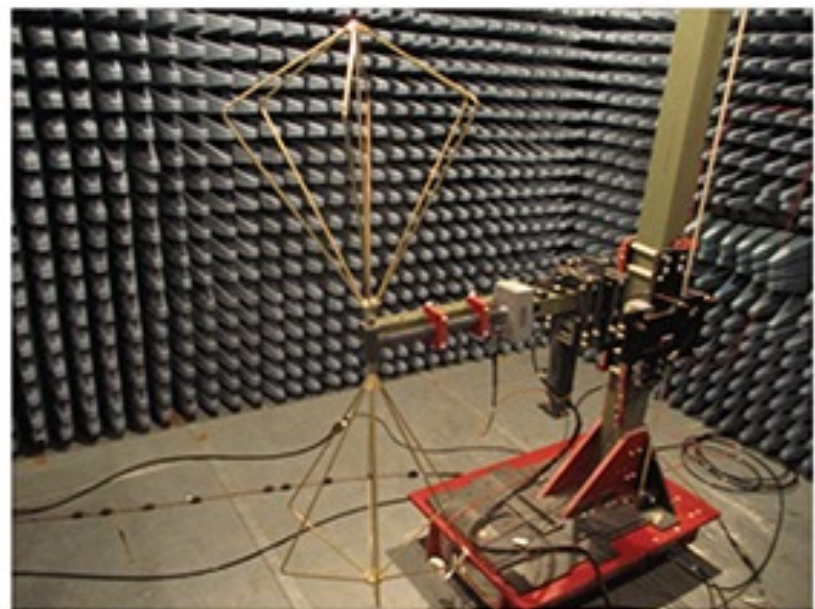
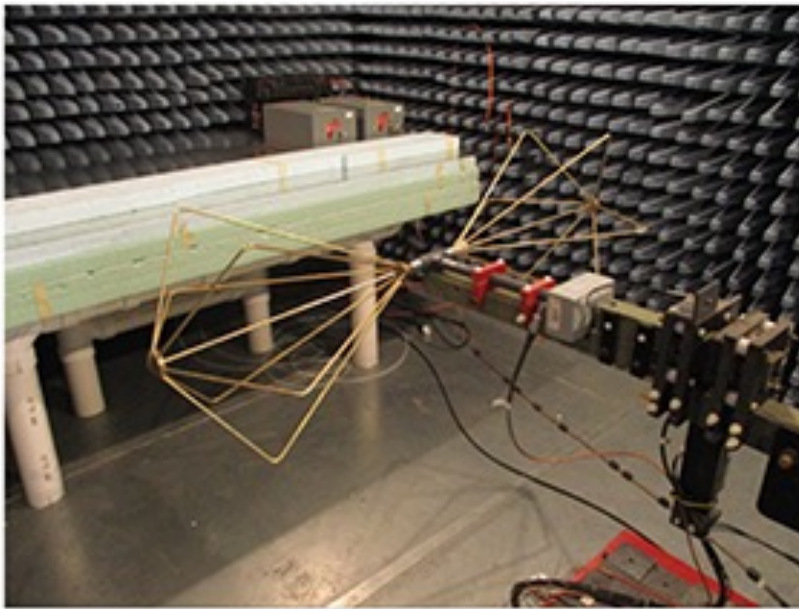
truncated biconical antenna
composed of wire elements

The Biconical Antenna in OATS EMC measurement



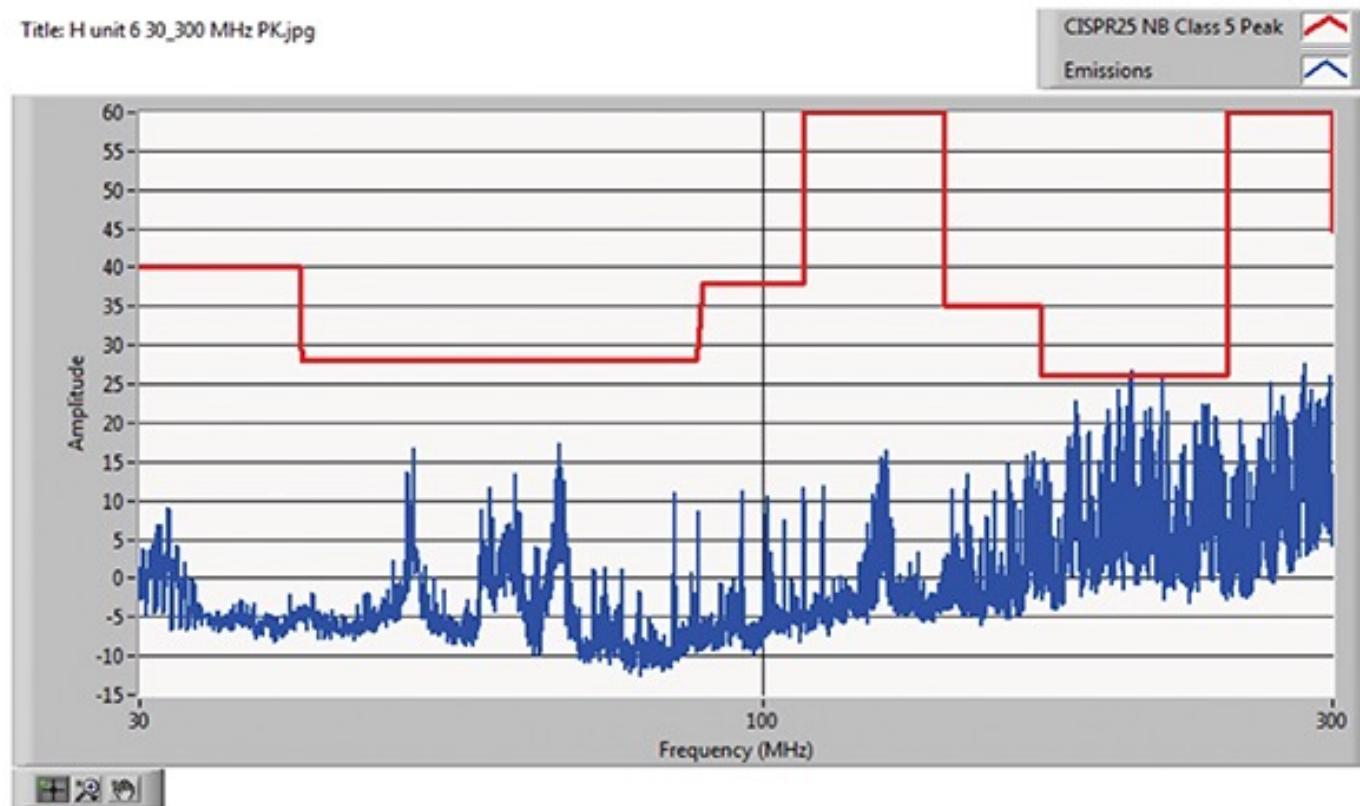
The outdoor set up for EMC measurement.
Open Area Test Site (OATS)

The Biconical Antenna in Anechoic Chamber

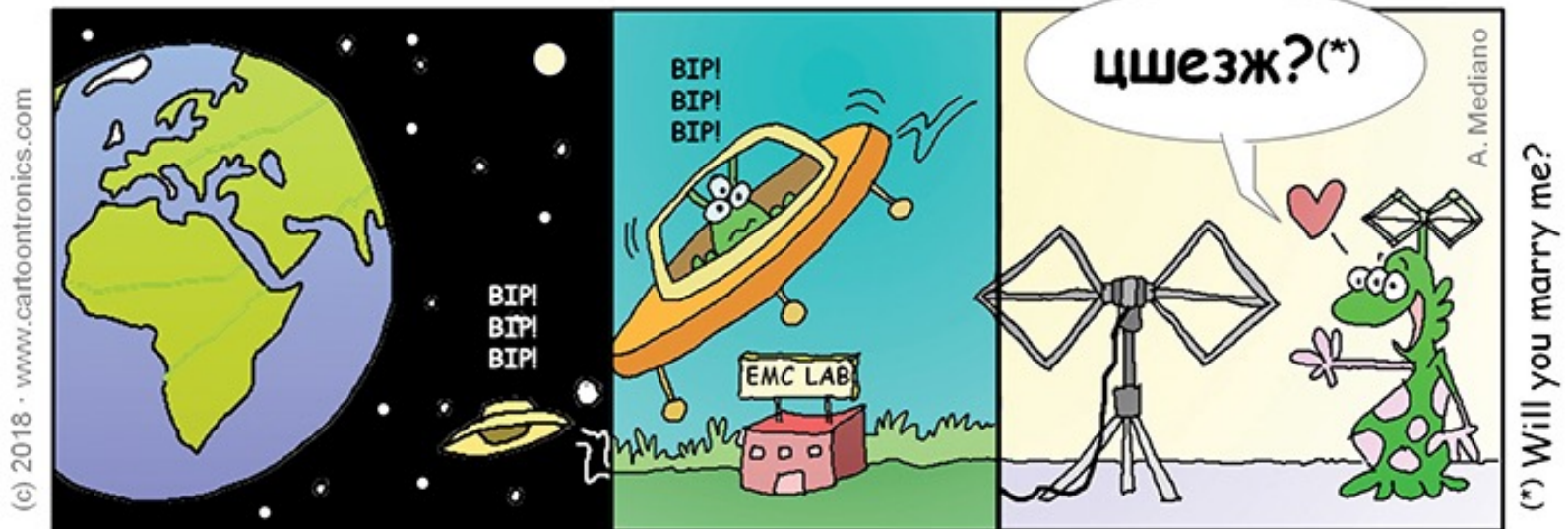


Biconical antenna polarization

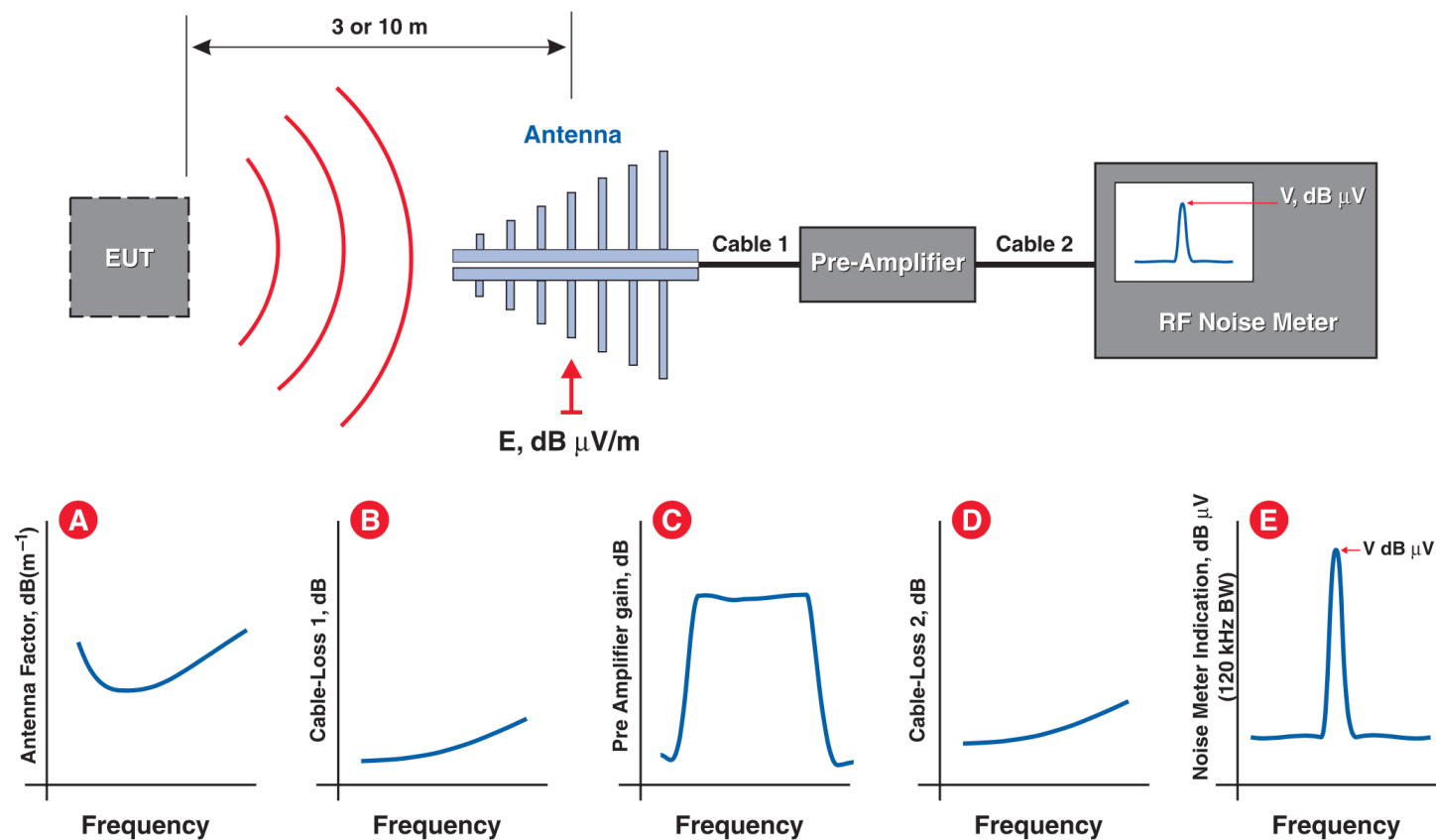
The Biconical Antenna in EMC measurement



Biconical antenna measurements results



Preview of Radiated Emission Test



$$E(\text{dB } \mu \text{ V/m}) = V(\text{dB } \mu \text{ V}) + CL_1(\text{dB}) - PAG(\text{dB}) + CL_2(\text{dB}) + AF(\text{dBm}^{-1})$$

6 Antenna Arrays

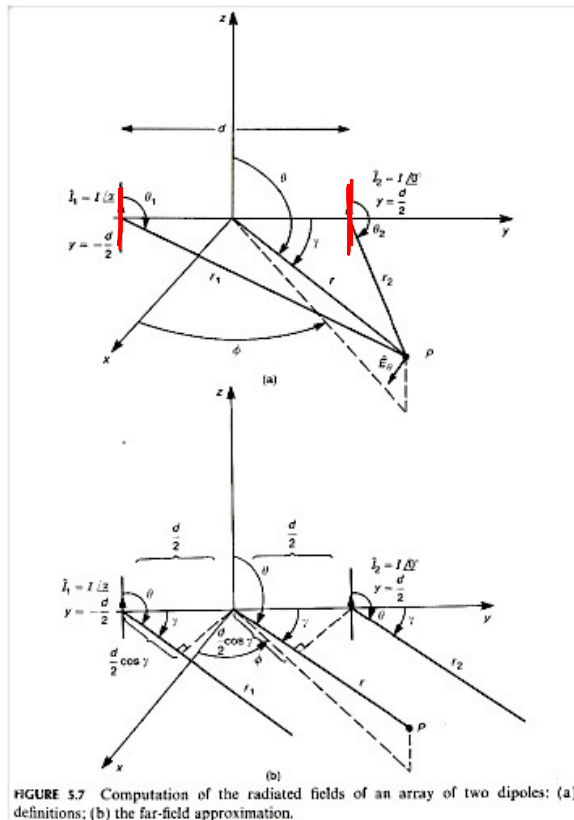


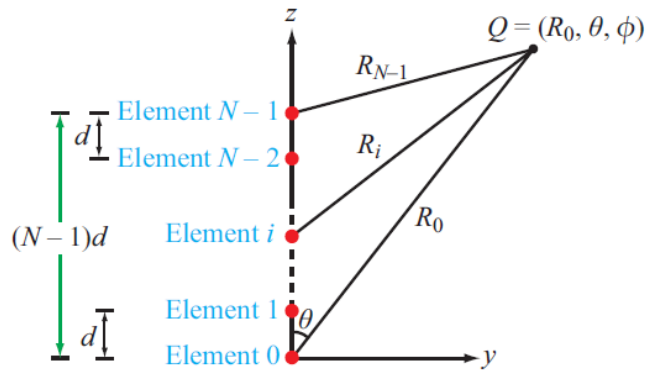
FIGURE 5.7 Computation of the radiated fields of an array of two dipoles: (a) definitions; (b) the far-field approximation.

- Hertzian dipole, small loop, half dipole, and monopole are all **omnidirectional** because of symmetry of the structure.
- Two or more omni-directional antennas can change the pattern (create null or maximum). Better both for **communication** and **EMI** considerations.
- This can be achieved by **phasing the currents** to the antennas and separated them sufficiently such that the fields will add **constructively and destructively** to result in the null/maximum patterns.

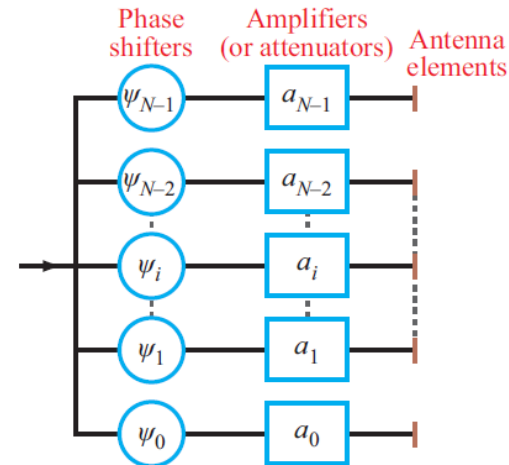
Antenna Arrays

- By using two or more omni-directional antennas to produce maxima and/or nulls in the resulting pattern (constructive/destructive).
- Suppose the E field due to each element antenna is

$$\hat{E}_\theta = \frac{\hat{M}I}{R} e^{-jk_0 R_0}$$



(b) Array geometry relative to observation point



(a) Array elements with individual amplitude and phase control
Linear-array configuration

- The far fields at point Q due to each antenna are of the form:

$$\hat{E}_{\theta 0} = \frac{\hat{M}I \angle 0}{R_0} e^{-jk_0 R_0}$$

$$\hat{E}_{\theta 1} = \frac{\hat{M}I \angle \alpha}{R_1} e^{-jk_0 R_1}$$

⋮

note:

1. $I_1 = I\angle 0$ and $I_2 = I\angle \alpha$ we assume that the currents of the two antennas are equal in magnitude but with phase difference α .
2. $\hat{M}$ depends on the type of antennas used.

for Hertzian dipole: $\hat{M} = j\eta_0 k_0 \left(\frac{dl}{4\pi} \right) \sin \theta$

for long dipole : $\hat{M} = j\epsilon_0 F(\theta)$

The total field at point Q

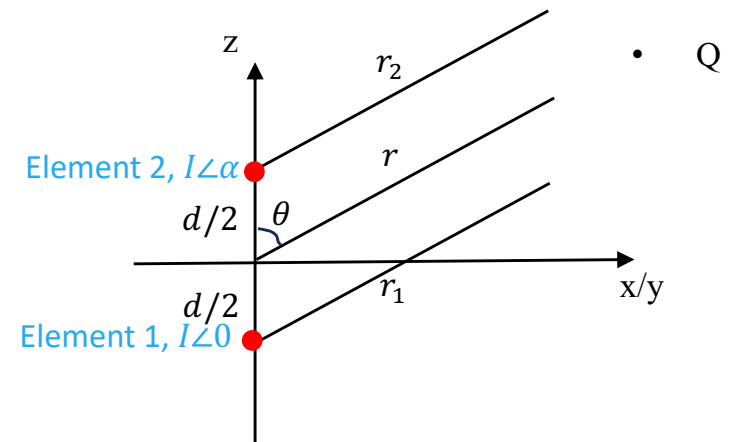
$$\hat{E}_\theta = \hat{E}_{\theta 1} + \hat{E}_{\theta 2} = \hat{M} I e^{\frac{j\alpha}{2}} \left(\frac{e^{-jk_0 r_1}}{r_1} e^{\frac{j\alpha}{2}} + \frac{e^{-jk_0 r_2}}{r_2} e^{-\frac{j\alpha}{2}} \right)$$

using for field approximation.

(1) $r_1 \cong r_2 \cong r$ for distance term.

$$(2) r_1 \cong r + \frac{d}{2} \cos \gamma \cong r + \frac{d}{2} \sin \theta \sin \phi$$

$$r_2 \cong r - \frac{d}{2} \cos \gamma \cong r - \frac{d}{2} \sin \theta \sin \phi, \text{ where } \cos \gamma = \vec{a}_r \cdot \vec{a}_y = \sin \theta \sin \phi$$



Parallel-ray approximation for 2D case.

$$r_1 \approx r + \frac{d}{2} \cos \theta,$$

$$r_2 \approx r - \frac{d}{2} \cos \theta$$

$$\begin{aligned}
\hat{E}_\theta &= \hat{E}_{\theta 1} + \hat{E}_{\theta 2} = \hat{M} I e^{\frac{j\alpha}{2}} \left(\frac{e^{-jk_0 r_1}}{r_1} e^{\frac{j\alpha}{2}} + \frac{e^{-jk_0 r_2}}{r_2} e^{-\frac{j\alpha}{2}} \right) \\
&= \frac{\hat{M} I}{r} e^{\frac{j\alpha}{2}} e^{-jk_0 r} \left(e^{j\left(k\left(\frac{d}{2}\right) \sin \theta \sin \phi - \frac{\alpha}{2}\right)} + e^{-j\left(k\left(\frac{d}{2}\right) \sin \theta \sin \phi - \frac{\alpha}{2}\right)} \right) \\
&= \left[\hat{M} \frac{I e^{-jk_0 r}}{r} \right] 2 e^{\frac{j\alpha}{2}} \cos \left(\frac{\pi d}{\lambda_0} \sin \theta \sin \phi - \frac{\alpha}{2} \right)
\end{aligned}$$

pattern of individual elements × $F_{array}(\theta, \varphi)$

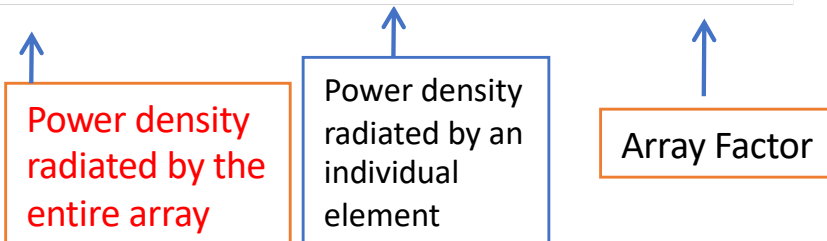
Array Factor

d. The principle of Pattern Multiplication:

The resultant field is the product of the individual antenna element and the array factor $F_{array}(\theta, \varphi)$.

For 1-D antenna array along z-axis

$$S(R_0, \theta, \phi) = S_e(R_0, \theta, \phi) F_a(\theta).$$



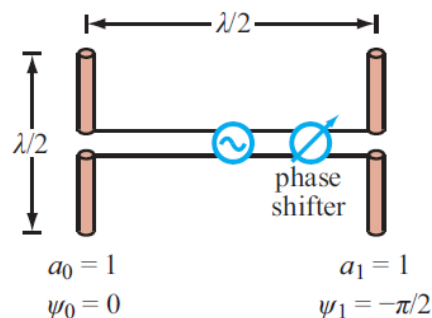
$$F_{array} = \left| \sum_{i=0}^{N-1} a_i e^{j\Psi_i} e^{j i k d \cos \theta} \right|^2$$

a_i : magnitude ratio between elements
 Ψ_i : phase shift between elements
 d : separation between elements in 1D

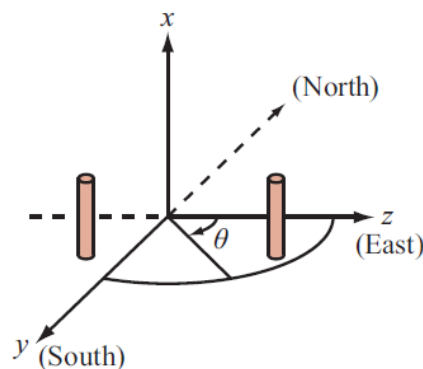


Example: Array of two vertical dipoles

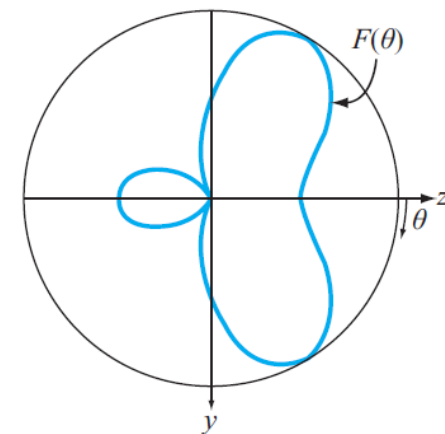
An AM radio station uses two vertically oriented half-wave dipoles separated by a distance of $\lambda/2$. The vector from the location of the first dipole to the location of the second dipole points toward the east. The two dipoles are fed with equal-amplitude excitations, and the dipole farther east is excited with a phase shift of $-\pi/2$ relative to the other one. Find and plot the antenna pattern of the antenna array in the yz plane.



(a) Dipole array



(b) Observation plane



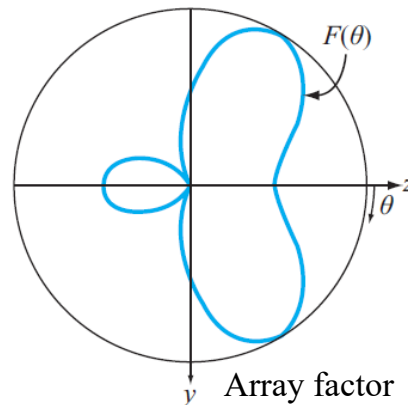
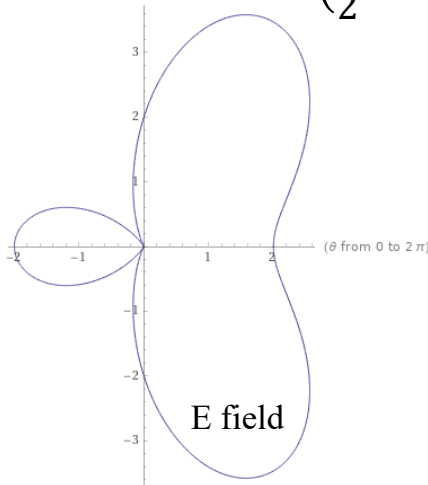
(c) Horizontal-plane pattern

Two half-wave dipole array

Example: Array of two vertical dipoles

Find and plot the antenna pattern of the antenna array in the yz plane.

$$\begin{aligned}
 |F_{array}| &= \left| \sum_{i=0}^1 a_i e^{j\Psi_i} e^{j i k d \cos \theta} \right|^2 \\
 &= \left| 1 + e^{-j\frac{\pi}{2}} e^{j\left(\frac{2\pi}{\lambda}\right)\left(\frac{\lambda}{2}\right) \cos \theta} \right|^2 \\
 &= \left| 1 + e^{j\left(\pi \cos \theta - \frac{\pi}{2}\right)} \right|^2 \\
 &= 4 \cos^2 \left(\frac{\pi}{2} \cos \theta - \frac{\pi}{4} \right)
 \end{aligned}$$



$$\rightarrow F_{a,max} = 4 \text{ when } \frac{\pi}{2} \cos \theta - \frac{\pi}{4} = 0, \cos \theta = \frac{1}{2}, \theta = \pm 60^\circ$$

In the yz plane, half-wave dipole radiates uniformly
 $\rightarrow S_e = S_0$

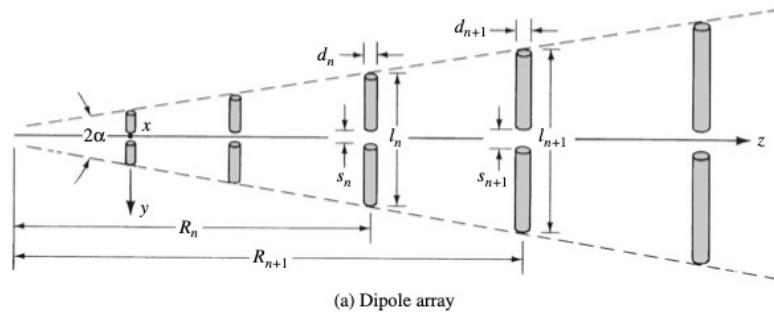
The power density radiated by the array is

$$S(R, \theta) = S_0 F_a(\theta) = 4S_0 \cos^2 \left(\frac{\pi}{2} \cos \theta - \frac{\pi}{4} \right)$$

normalized radiation intensity is

$$F(\theta) = \frac{S_R(\theta)}{S_{max}} = \cos^2 \left(\frac{\pi}{2} \cos \theta - \frac{\pi}{4} \right)$$

Log-Periodic Dipole Array (LPDA) Antenna



Scale factor

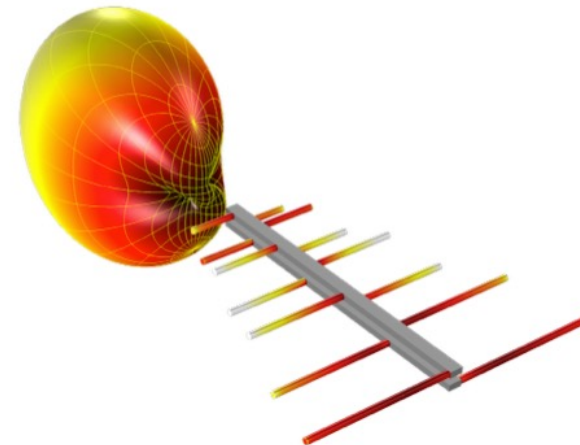
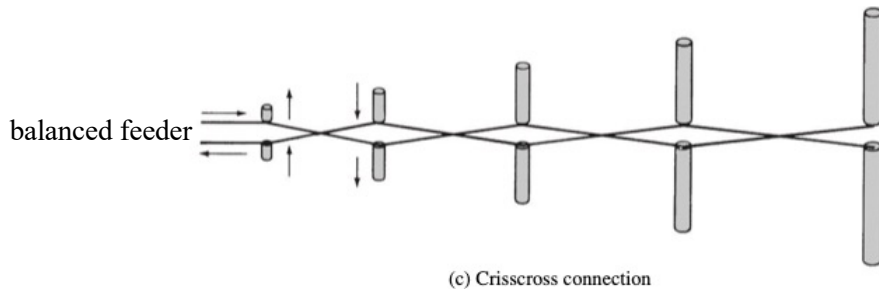
$$\tau = \frac{l_{n+1}}{l_n} = \frac{d_{n+1}}{d_n}$$

constant



Element length L_n
and separation d_n

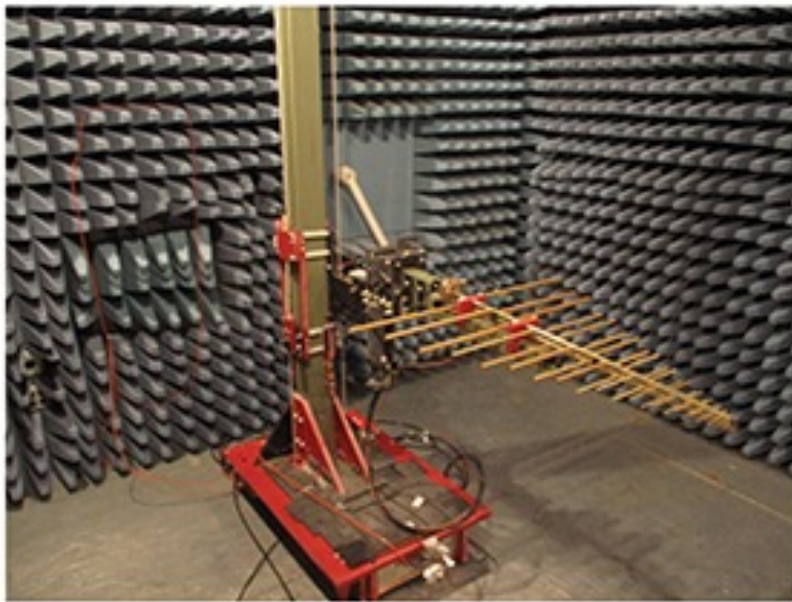
LPDA is constructed as below



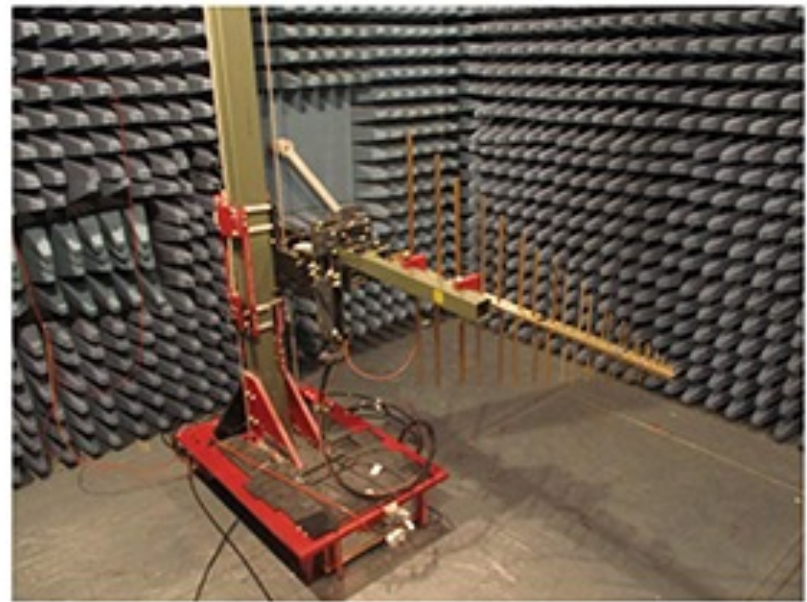
(b) Radiation pattern

The most common form of log-periodic antenna used for the measurement of radiated emissions from 200 MHz to 1 GHz is the log-periodic dipole array.

Log-periodic antenna polarization in EMC measurement

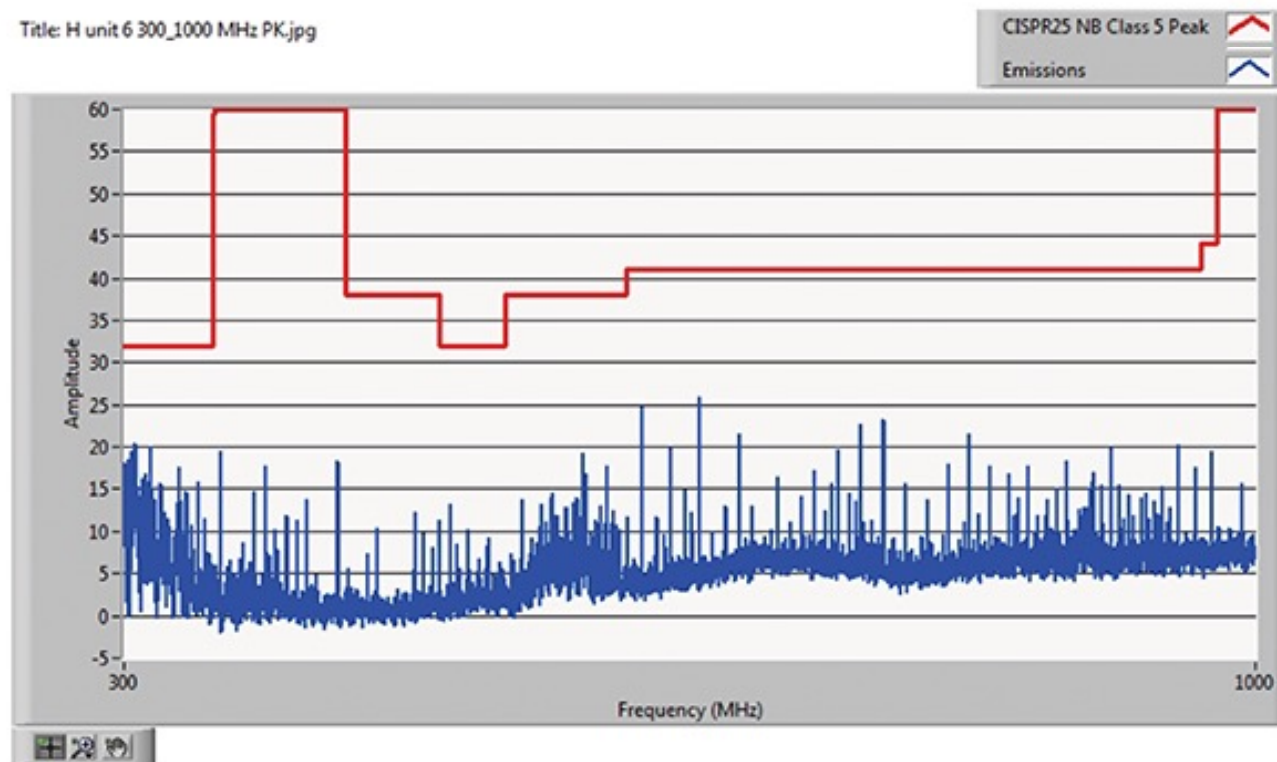


Horizontal polarization



Vertical polarization

The Log-periodic Antenna in EMC measurement

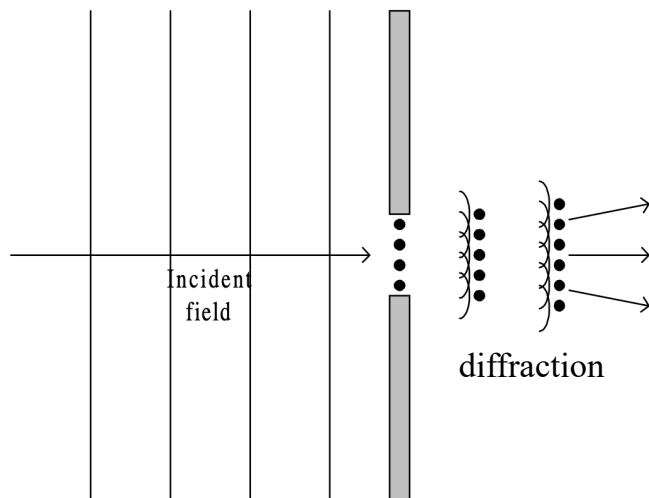


Log-periodic antenna measurements results

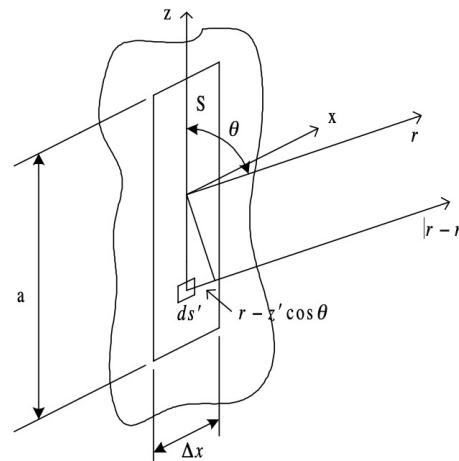
Aperture antennas

Huygen's principle:

- Each point in an advancing wavefront acts as a source of spherical, secondary wavelets, that propagate outward.
- The secondary wavelets cause the wave to spread as it travels away from the aperture.



diffraction



Radiation from a narrow aperture

