Linear Antennas

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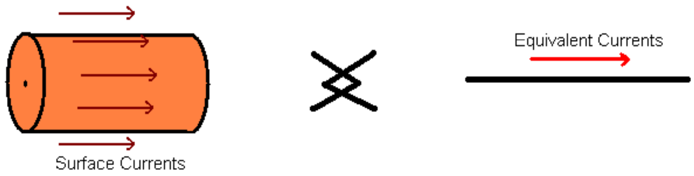
Outline

1.- Introduction
2.- The electric dipole, Baluns
3.- Monopole over ground plane
4.- Dipoles Parallel to the ground plane
5.- Yagi-Uda Antennas
6.- Other linear antennas

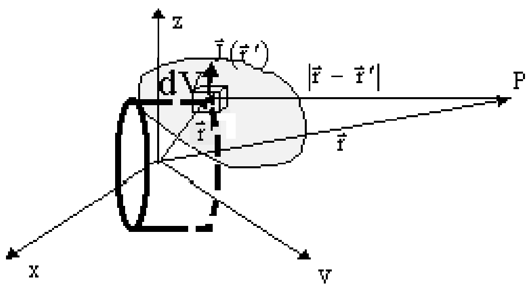
Linear Antennas

- Linear antennas are considered to be those antennas that imply the use of electrically thin conductors (wavelength >>conductor diameter).
- Electric current flows over the conductor surface.
- In order to calculate radiated fields in these antennas, conductors are modeled as if they were current lines with no diameter. Its equivalent current is the surface current of the real model.



Linear Antennas

- Paying attention to the geometry, it is necessary to calculate the potential vector



Potential Vector:

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{L'} \frac{I(\vec{r}\,')e^{-jk_0|\vec{r}-\vec{r}\,'|}}{|\vec{r}-\vec{r}\,'|}d\vec{l}\,'$$

Potential Vector $(\vec{r}\,' << \vec{r})$:

$$\vec{A} = \frac{\mu}{4\pi}\frac{e^{-jkr}}{r}\int_{L'} I(\vec{r}\,')e^{jk\hat{r}\cdot\vec{r}\,'}d\vec{l}\,'$$

- Potential vector allows us to obtain the electric field distribution:

$$\vec{H} = \frac{1}{\mu_0}\nabla\times\vec{A} \qquad \vec{E} = \frac{1}{j\omega\varepsilon_0}\nabla\times\vec{H}$$

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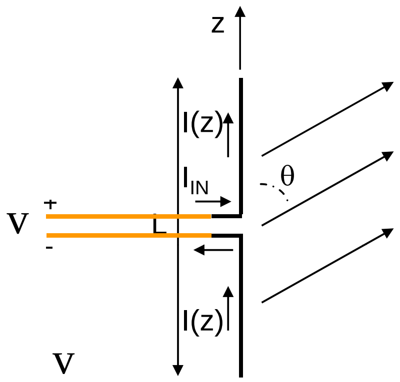
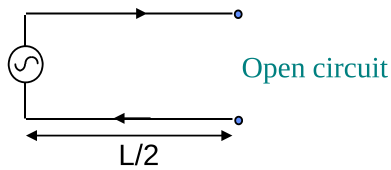
$\frac{L}{2}$

The electric dipole

- Mainly, an electric dipoles formed by two $\frac{L}{2}$ wires working together.



Although it is possible to calculate the analytical current distribution over the structure, it is preferable to assume some approximate results using *Transmission line theory*



In that conditions, we obtain the current distribution

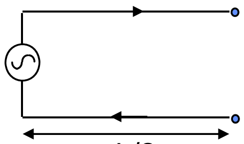
$$I(z) = I_m \sin\left[k\left(\frac{L}{2} - |z|\right)\right] \quad |z| < \frac{L}{2}$$

The electric dipole

$$I(z) = I_m \sin\left[k\left(\frac{L}{2} - |z|\right)\right] \quad |z| < \frac{L}{2}$$

Feeding current:

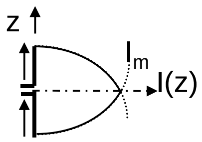
$$I_{IN} = I_m \sin\left[k\frac{L}{2}\right] \longrightarrow I_m = \frac{I_{IN}}{\sin\left[k\frac{L}{2}\right]}$$



• The model yields a quite good agreement with the analytical result when considering $L = \frac{\lambda}{2}$

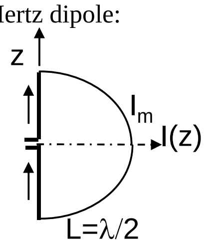
Current distribution for different dipole lengths:

Short dipole:



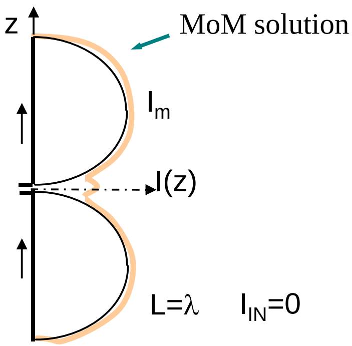
L<λ/2

Hertz dipole:



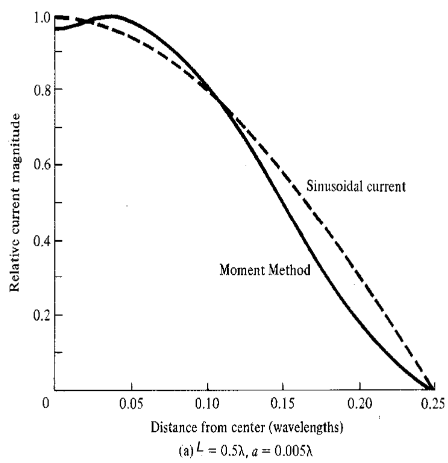
L=λ/2

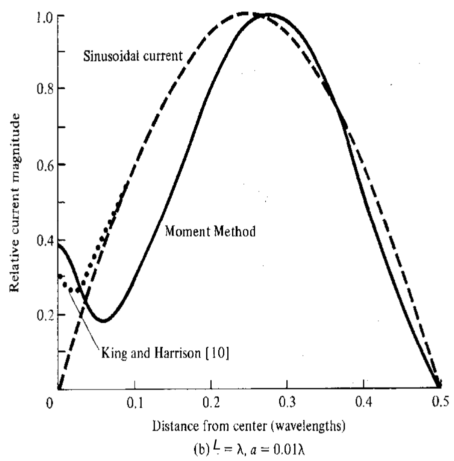
$I_{IN}=I_m$



L=λ $I_{IN}=0$

The electric dipole





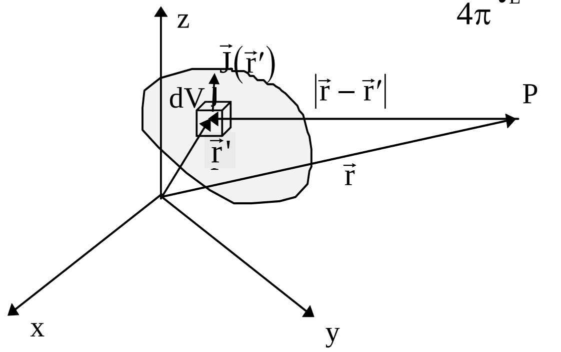
Current distributions calculated using Moment Method

Radiated Field

Infinitesimal Dipole

Potential Vector:

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{L'} \frac{I(\vec{r}')e^{-jk_0|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}\,d\vec{l}'$$



$$\vec{H} = \frac{1}{\mu_0}\nabla\times\vec{A}$$

$$\vec{E} = \frac{1}{j\omega\varepsilon_0}\nabla\times\vec{H}$$

Electric and magnetic fields:

$$\vec{H} = \hat{\phi}\left[\frac{\partial}{\partial r}(rA_\theta) - \frac{\partial}{\partial\theta}A_r\right] = \hat{\phi}\,\frac{Idl\,sen\theta}{4\pi r}\left(jk_0 + \frac{1}{r}\right)e^{-jk_0 r}$$

$$\vec{E} = \frac{j\eta Idl}{2\pi k_0}\left[\hat{r}\cos\theta\left(\frac{jk_0}{r^2} + \frac{1}{r^3}\right) + \hat{\theta}\,\frac{sen\theta}{2}\left(-\frac{k_0^2}{r} + \frac{jk_0}{r^2} + \frac{1}{r^3}\right)\right]e^{-jk_0 r}$$

Radiated Field

Finite Dipole

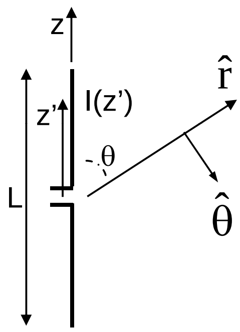
Coordinates:

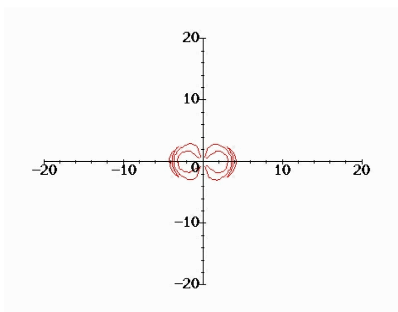
$$|\hat{r}-\vec{r}'| = r - z'\cos\theta + \frac{1}{r}\left(\frac{z'^2}{2}\sin^2\theta\right) + \frac{1}{r^2}\left(\frac{z'^3}{2}\cos\theta\sin^2\theta\right) + \dots$$

potential vector:

$$\vec{A} = \frac{\mu}{4\pi}\int \frac{I(\vec{r}')e^{-jk\cdot|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}\,d\vec{l}' =$$

$$= \frac{\mu}{4\pi}\int_{-L/2}^{L/2} \frac{I_m sen\left(k\left(\frac{L}{2}-|z|\right)\right)}{r - z'\cos\theta + \frac{1}{r}\left(\frac{z'^2}{2}\sin^2\theta\right) + \frac{1}{r^2}\left(\frac{z'^3}{2}\cos\theta\sin^2\theta\right) + \dots}\, e^{jkr - z'\cos\theta + \frac{1}{r}\left(\frac{z'^2}{2}\sin^2\theta\right) + \frac{1}{r^2}\left(\frac{z'^3}{2}\cos\theta\sin^2\theta\right) + \dots}\,\hat{z}dz'$$





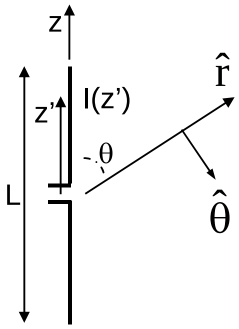
Electric field: $|E| \propto K_1 \cdot \left(\frac{1}{k_2 r} + \frac{1}{k_3 r^2} + \dots\right)$

Radiated Field

Finite Dipole

Coordinates: $\hat{r}\cdot\vec{r}\,' = \left(\mathrm{sen}\,\theta\cos\phi\;\hat{x} + \mathrm{sen}\,\theta\,\mathrm{sen}\,\phi\;\hat{y} + \cos\theta\hat{z}\right)\cdot\left(z'\hat{z}\right) = z'\cos\theta$

Far potential vector: $\vec{A} = \frac{\mu}{4\pi}\frac{e^{-jkr}}{r}\int_{L'} I(\vec{r}\,')e^{jk\hat{r}\cdot\vec{r}\,'}d\vec{l}\,' =$



$$= \frac{\mu}{4\pi}\frac{e^{-jkr}}{r}\int_{-L/2}^{L/2} I_m sen\left(k\left(\frac{L}{2}-|z|\right)\right)e^{jkz'\cos\theta}\hat{z}dz' =$$

$$= \frac{\mu}{4\pi}\frac{e^{-jkr}}{r}\frac{2I_m}{k}\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{sen^2\theta}\left(\underbrace{\cos\theta\hat{r}-sen\theta\hat{\theta}}_{\hat{z}}\right)$$

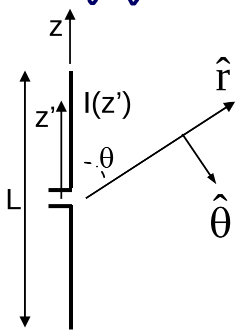
Could be considered as a 1st order approximation

Far field: $\vec{E} = -j\omega\left(A_\theta\hat{\theta}+A_\phi\hat{\phi}\right) = j\eta\frac{e^{-jkr}}{2\pi r}I_m\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\mathrm{sen}\,\theta}\hat{\theta}$

$E_\phi = 0$

Linear Polarization throughout θ

Radiated Power

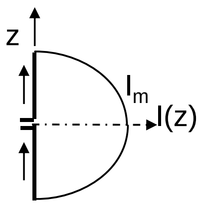


$$\vec{E} = -j\omega\left(A_\theta\hat{\theta}+A_\phi\hat{\phi}\right) = j\eta\frac{e^{-jkr}}{2\pi r}I_m\frac{\cos\left(\frac{kL}{2}\cos\theta\right)-\cos\left(\frac{kL}{2}\right)}{\sin\theta}\hat{\theta}$$

$$P_{rad} = \int_{4\pi}U(\theta,\phi)d\Omega = \iint r^2\frac{|E(\theta,\phi)|^2}{2\eta_0}\sin(\theta)d\theta d\phi$$

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

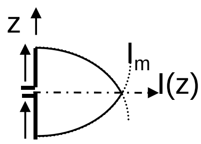
Hertz dipole:



$$P_{rad} = \frac{\pi}{3}\eta_0|I_0|^2\left(\frac{l}{\lambda}\right)^2$$

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

Short dipole:



$$P_{rad} = \frac{\pi}{12}\eta_0|I_0|^2\left(\frac{l}{\lambda}\right)^2 = \frac{p_{hertz}}{4}$$

$$R_{rad} = 20\pi^2\left(\frac{l}{\lambda}\right)^2$$

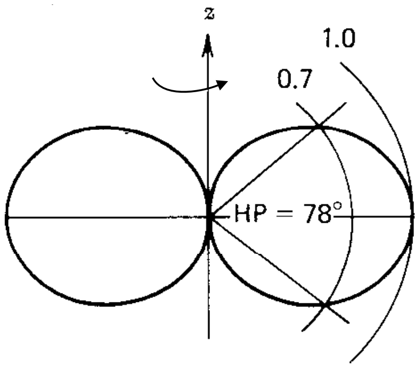
Radiation Parameters

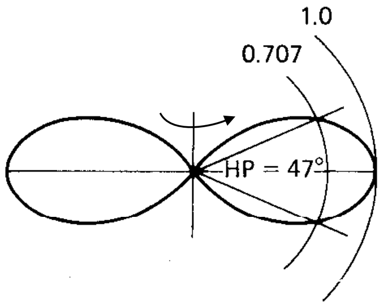
Normalized Field diagrams:

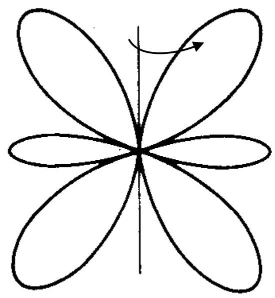
$$\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\operatorname{sen}\theta}$$

$$\frac{1+\cos(\pi\cos\theta)}{2\operatorname{sen}\theta}$$

Multilobe Diagram



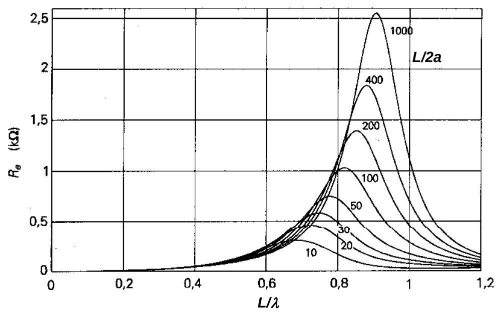


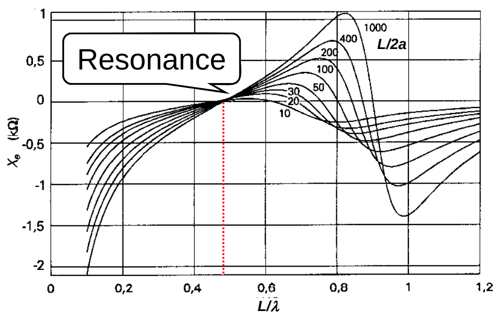


	L=0.5λ	L=λ	L=1.5λ
Directivity:	D_0=1,64 = 2,15 dBi	D_0=2,41	D_0=2,17
$R_{radiation}$:	R_{rad}=73 Ω	R_{rad}=∞ Ω	R_{rad}=99,5 Ω

Input Impedance

Input impedance: ($Z_{IN}=R_e+jX_e$)

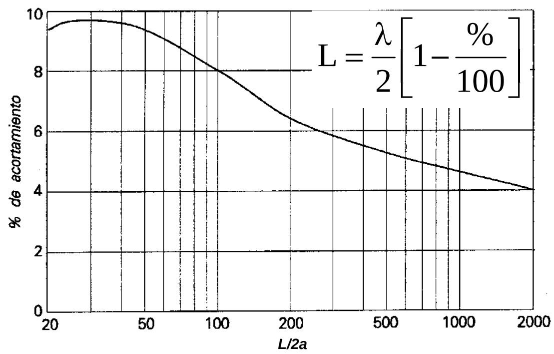




$Z_{IN}(\lambda/2)$=73+j42,5 Ω when a → 0

a=dipole radius

Resonance Condition



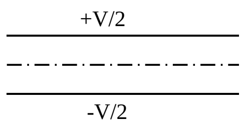
Dipole Feeding - Baluns

– Baluns are devices that transform balanced current lines into unbalanced ones. Its name comes from: “**balun**” = **bal**anced to **un**balanced.

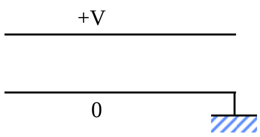
– Baluns allow us to feed symmetric structures in a balanced way.

For instance: dipoles, fed with asymmetric transmission lines, coaxial wires… Used to transport energy from circuitry to the antenna.

Balanced lines:



Unbalanced lines:



Bifilar

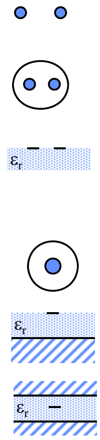
Shielded Bifilar

Coplanar

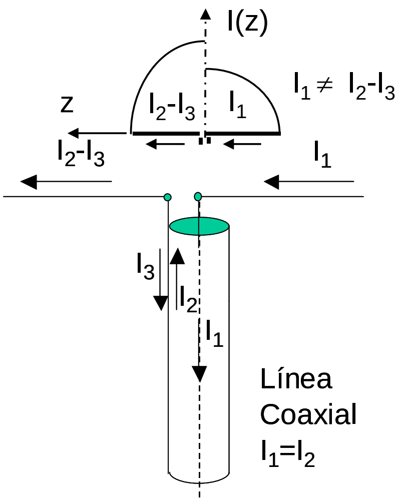
Coaxial

Microstrip

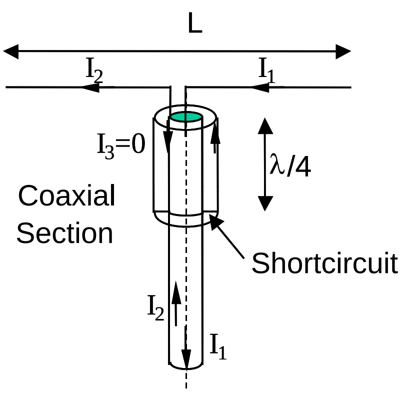
Stripline



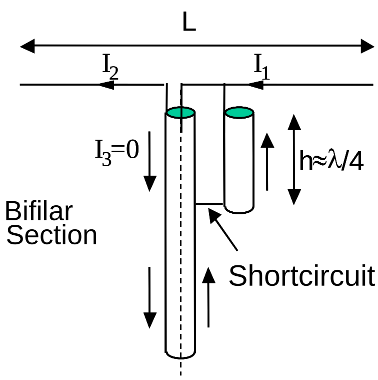
Baluns



Non symmetric feeding

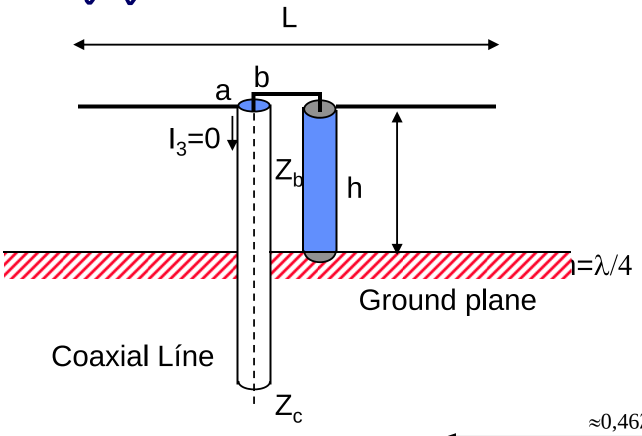


Bazooka or Sleeve Balun

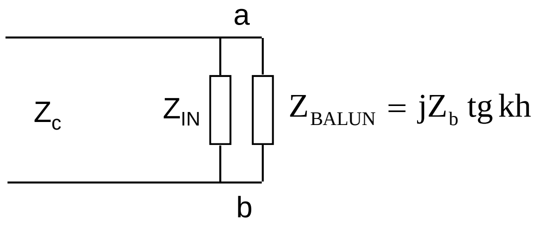


Broken Balun

Baluns



Equivalent Circuit



For $h=\lambda/4$ => $Z_{BALUM}= \infty$

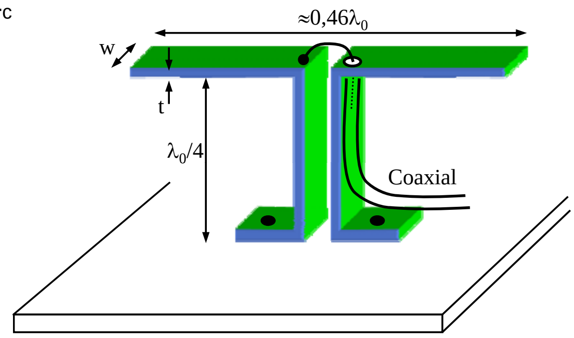


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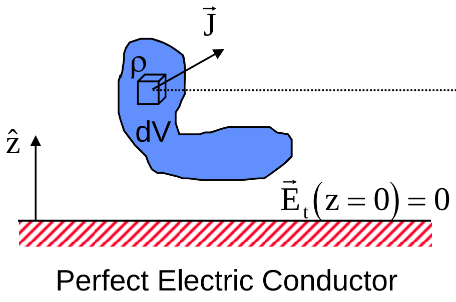
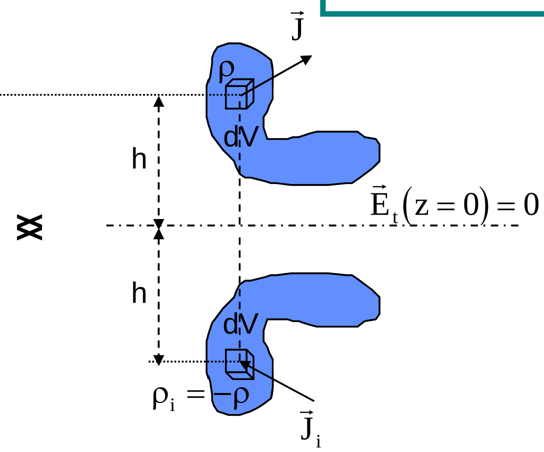
Image Theorem

z ≥0 Valid Results

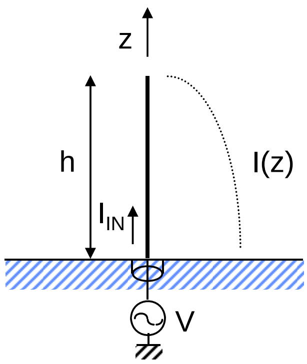


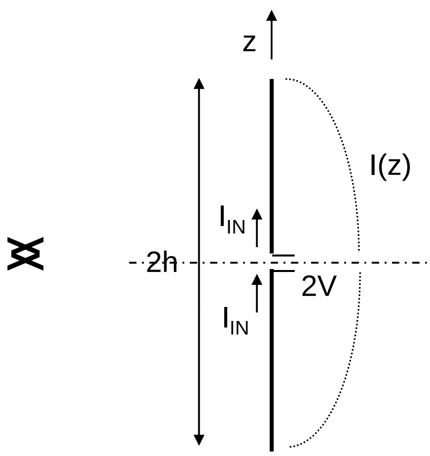


Sources and Image Currents

$$\begin{cases} \rho \\ \rho_i = -\rho \end{cases} \qquad \begin{cases} \vec{J} = J_x\hat{x} + J_y\hat{y} + J_z\hat{z} \\ \vec{J}_i = -J_x\hat{x} - J_y\hat{y} + J_z\hat{z} \end{cases}$$

Vertical Monopole over Ground Plane





$$D_d = 4\pi \frac{U_d}{P_d}$$

$$D_m = 4\pi \frac{U_m}{P_m} \leftarrow \begin{cases} U_m = U_d & (0 \le \theta \le \pi/2) \\ U_m = 0 & (\pi/2 \le \theta \le \pi) \end{cases}$$

$$P_m = \int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} U_m(\theta,\phi)\,\mathrm{sen}\,\theta\, d\theta\, d\phi = \frac{1}{2}P_d$$

$$Z_{INdipolo} = \frac{2V}{I} = 2Z_{INMonopolo}$$

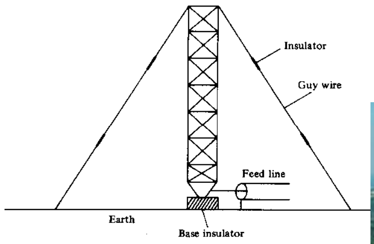
$$D_{monopolo} = 2D_{dipolo}$$

$$R_{rad\ monopolo} = \frac{1}{2} R_{rad\ dipolo}$$

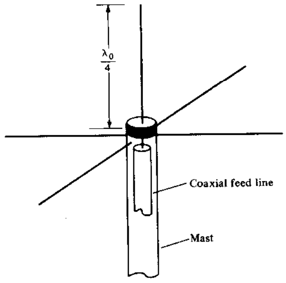
$$Z_{INmonopolo} = \frac{1}{2} Z_{INdipolo}$$

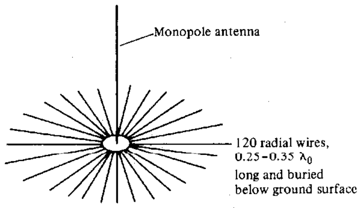
Vertical Monopoles

MW Monopole over ground.



Monopole over ground plane simulated with metallic wires





Typical Radiation Pattern

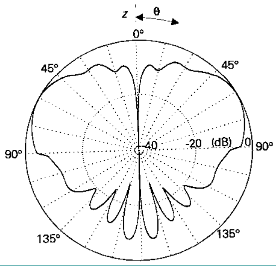


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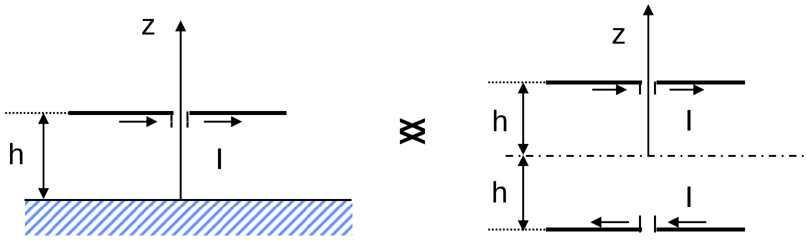
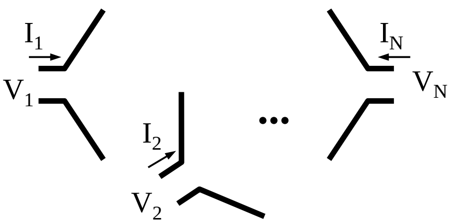
Image Theorem: parallel dipoles over ground plane



- When h<<λ, the radiated field is quite small due to the destructive summation of direct and reflected field.
- When h=λ/4 the radiated field is enhanced due to constructive summation in z direction.
- Considering finite ground planes (higher than λ x λ), the image theorem can be applied and undesired effects can be neglected.

Antenna mutual couplings

- When designing composed antenas, with several radiating elements, it is necessary to study mutual couplings between these elements.
  - From both, the radiation point of view (feeding currents) and the circuit point of view (impedance), the global antenna behaves as a **multiport linear network.**

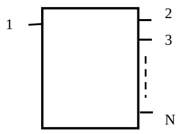


$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1N} \\ Z_{21} & Z_{22} & \cdots & Z_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \cdots & Z_{NN} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}$$

Active impedance of *i* radiating element:

$$Z_i = \frac{V_i}{I_i} = \sum_{j=1}^{N} Z_{ij} \frac{I_j}{I_i} = Z_{ii} + \sum_{\substack{j=1 \\ i \neq j}}^{N} Z_{ij} \frac{I_j}{I_i}$$

Easily related to generalized multipole analysis



Mutual Impedances between Dipoles

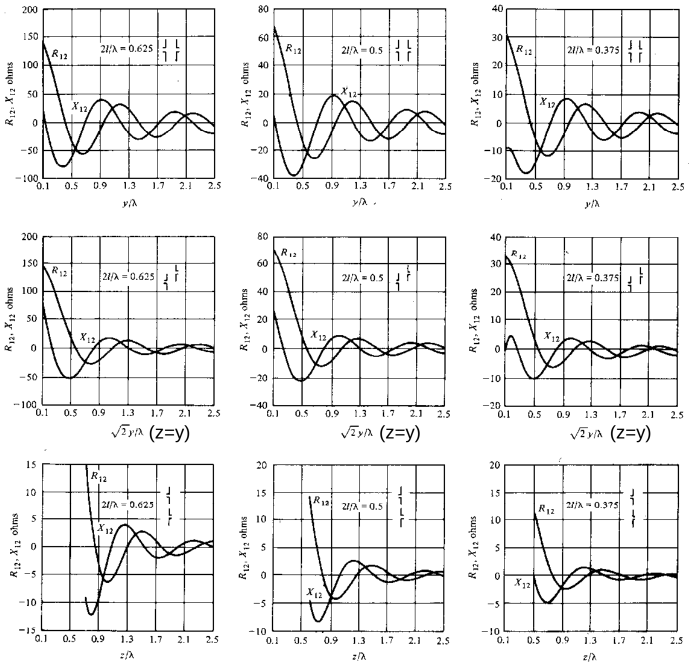
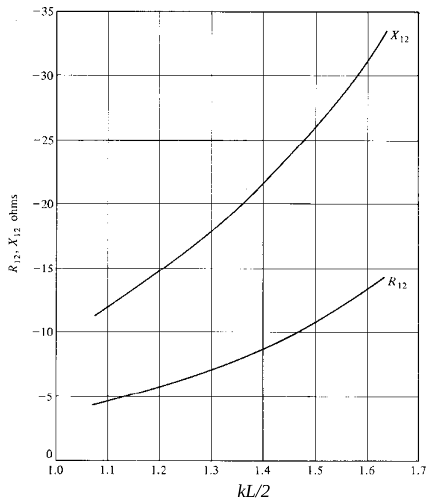


Fig. 7.24 The Mutual Impedance Between Two Identical Slender Center-Fed Cylindrical Dipoles versus Their Separation Along Various Paths; Rectangular Plots



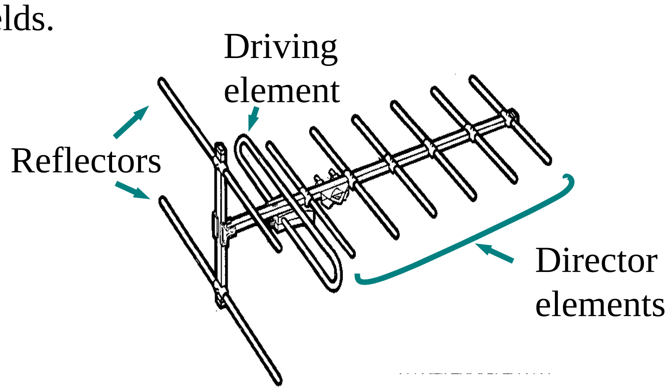
Mutual impedance between two identical parallel dipoles, one in front of the other, at $\lambda/2$ distance

Linear Antennas

1.- Introduction
2.- The electric dipole, Baluns
3.- Monopole over ground plane
4.- Dipoles Parallel to the ground plane
5.- Yagi-Uda Antennas
6.- Other linear antennas

Yagi Antennas

- These antennas are made of a lot of dipoles. Typically, only one of them is externally fed (active, driving element); the rest have induced currents due to mutual couplings (director elements).
- Passive dipoles behave whether reflecting (reflectors) or guiding (director elements) radiated fields.



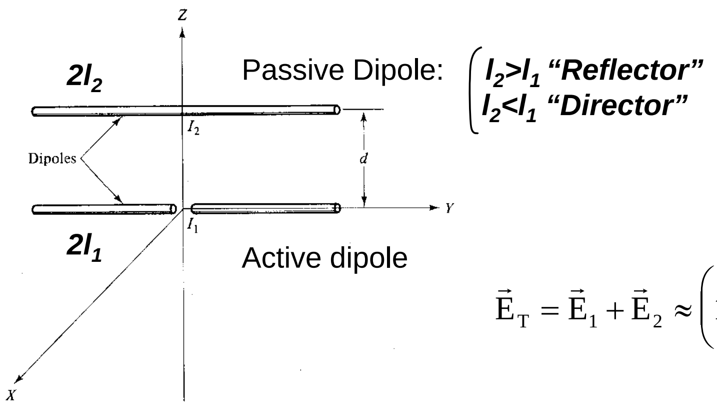
A Yagi antenna shows a radiation Gain, approximated by:

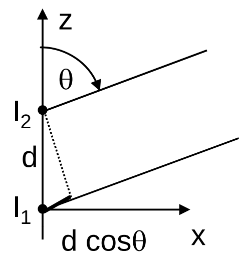
$$G_{yagi} = G_{Dipole} + 10\log(n+1)$$

where n is the number of driving dipoles.

Yagi Antennas

- 2 elements Yagi-Uda antenna.





$$\vec{E}_T = \vec{E}_1 + \vec{E}_2 \approx \left(1 + \frac{I_2}{I_1} e^{jkd\cos\theta}\right) \cdot \vec{E}_d(\theta,\phi)$$

- Circuital equations:

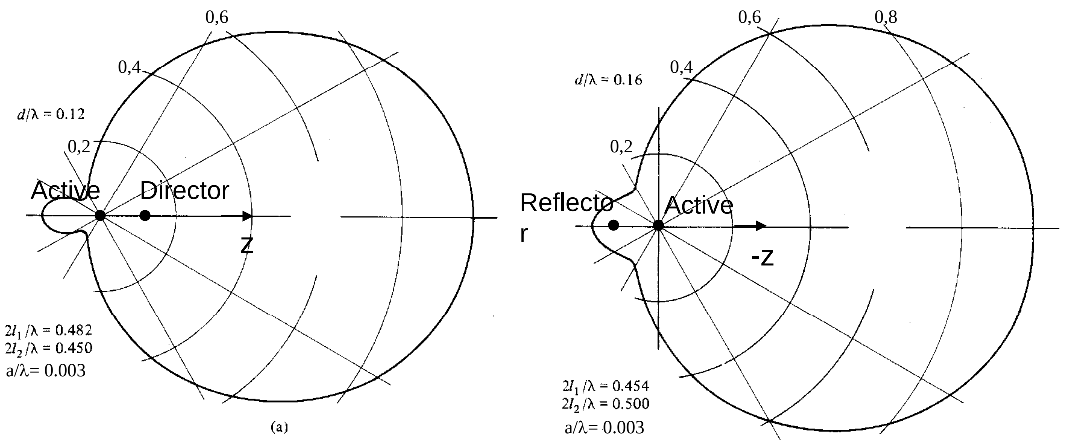
$$\begin{cases} V_1 = Z_{11}I_1 + Z_{12}I_2 \\ 0 = Z_{21}I_1 + Z_{22}I_2 \end{cases}$$

$$\boxed{\frac{I_2}{I_1} = -\frac{Z_{12}}{Z_{22}}}$$

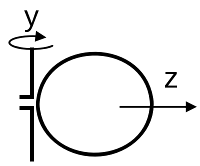
$$\boxed{Z_{IN} = \frac{V_1}{I_1} = Z_{11} - \frac{Z_{12}^2}{Z_{22}}}$$

2 elements Yagi Antenna: Patterns

H Plane (XZ Plane): $E_d(\theta,\phi=0)$=constant; $F(\theta,\phi=0)=|1+I_2/I_1 \exp(jkd\cos\theta)|$

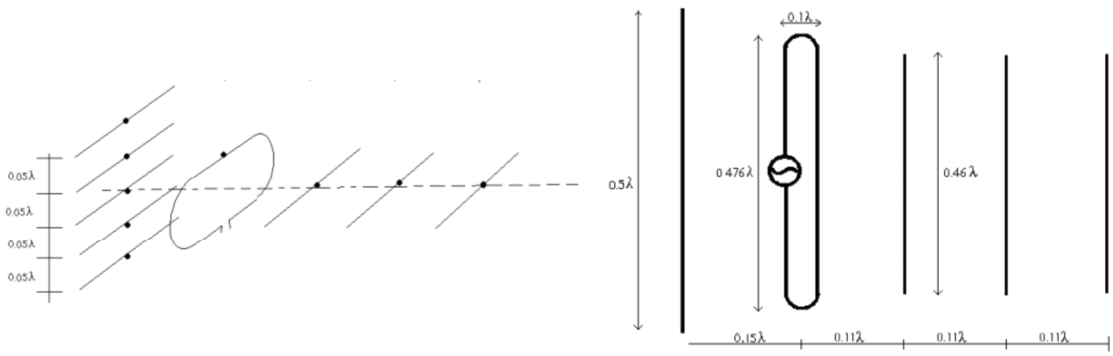


E Plane (YZ Plane): The radiation patter must include the dipole radiation pattern (like a donut).

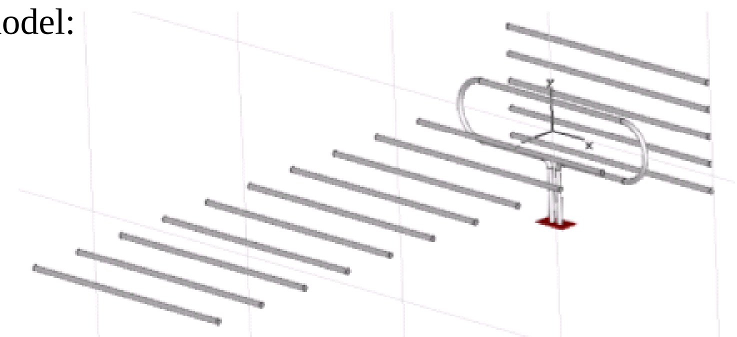


Yagi antennas.

Typical dimensions:



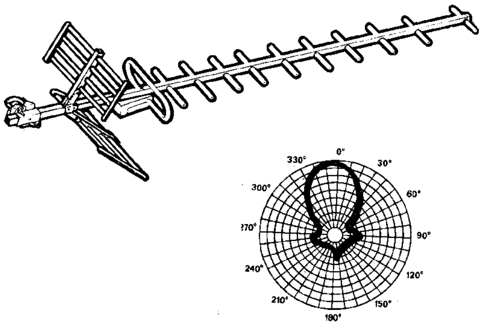
Simulation model:



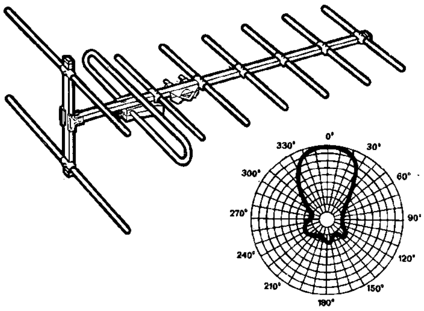
Yagi Examples

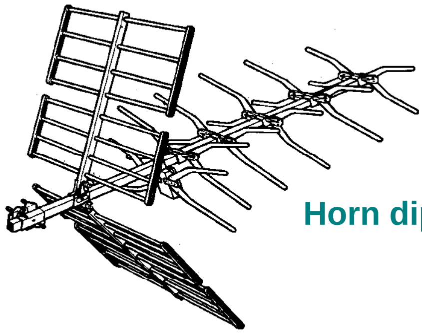
Usually, as active element, it is used a bended dipole in order to increase input impedance and band width.

Diedric reflector Yagi



Double reflector Yagi





Horn dipoles Yagi

Linear Antennas

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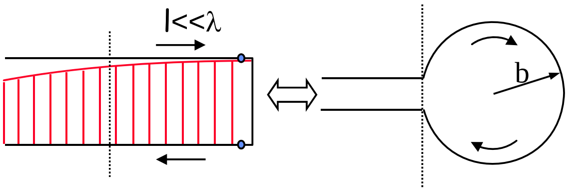
Loop Antennas

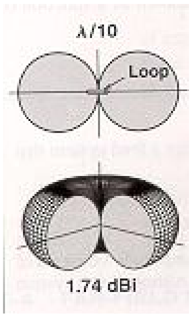
Aproximate current distribution:

Short Loop (in terms of λ):

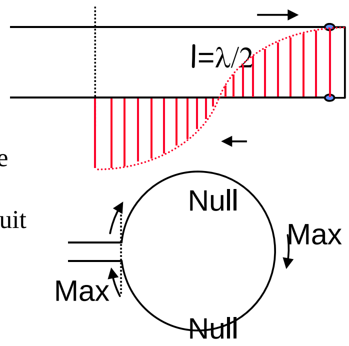
Short line with shortcircuit = **uniform current**



$C = 2\pi b \approx 2\ell$



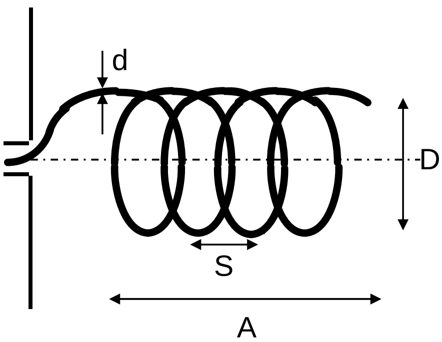
Large Loop (in terms of λ):

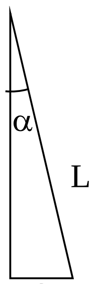


•multilobe pattern, high efficiency.

Helix

- The helix geometry depends on the next values:
  - D= Helix diameter.
  - C= Perimeter of the helix cylinder= πD
  - S= length of one turn= πD tanα
  - α= Inclination angle= atan(S/C)
  - L= one turn length
  - N= Number of turns.
  - A= Total length= NS
  - d= Wire diameter





- Helix antennas are usually used in its axial radiation mode, when C is similar to λ.

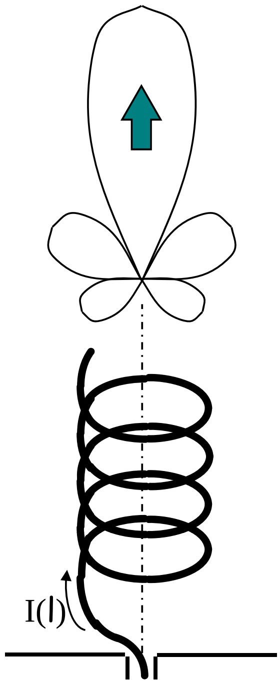
Helix
Axial Radiation Mode

- Electrically big helix, with dimensions $3/4 < C/\lambda < 4/3$ y $\alpha \approx 12º\text{-}15º$:
  - Progressive current wave through the helix: $I(l) = I_0 \exp(-jkl)$
  - Wide band: $f_{sup}/f_{inf} = 1{,}78$
  - Approximately real impedance value:

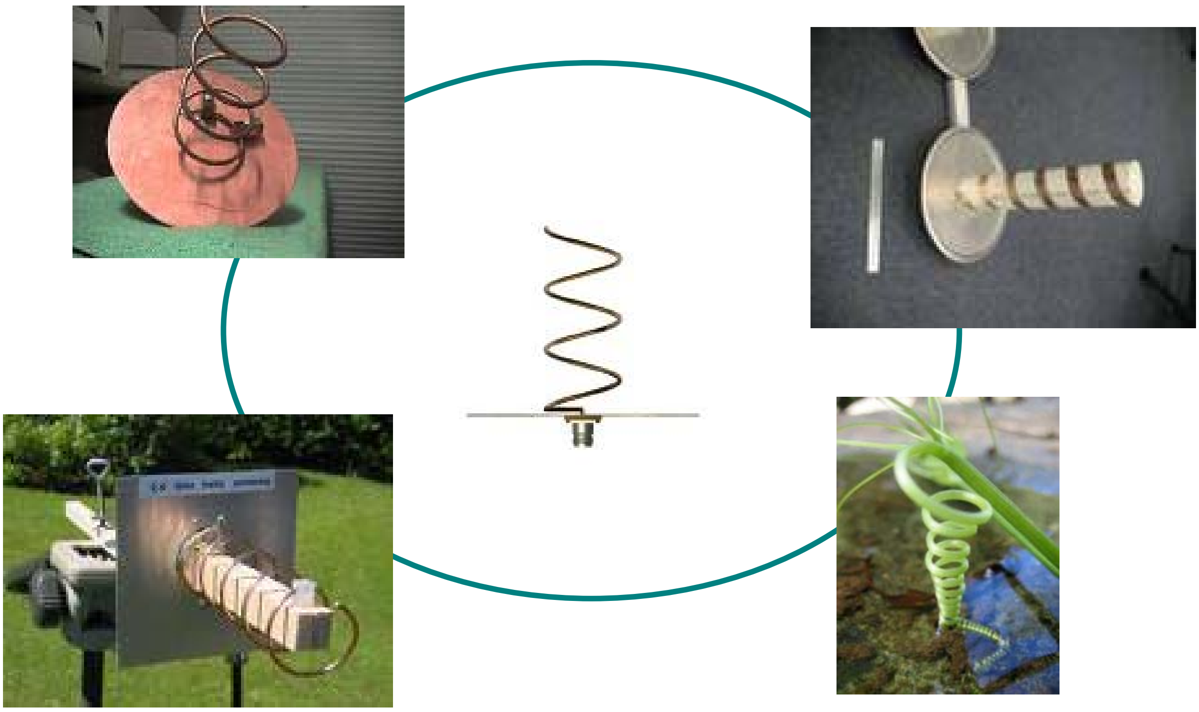
$$R_{in} \approx 140 \frac{C}{\lambda} \approx 140 \quad \Omega$$

  - Circular polarization (left or right handed, the same as the wire turn)
  - Quite directive radiation pattern. Secondary lobe level: -9 dB.
  - Directivity:

$$D \approx 15 \left(\frac{C}{\lambda}\right)^2 \frac{NS}{\lambda} \approx 15 \frac{A}{\lambda}$$



Helix examples



ANTENNA DESIGN AND MEASUREMENT TECHNIQUES - Madrid (UPM) – March 2009