Travelling Wave, Broadband, and Frequency Independent Antennas

EE-4382/5306 - Antenna Engineering

Outline

- Traveling Wave Antennas
  - Introduction
  - Traveling Wave Antennas: Long Wire, V Antenna, Rhombic Antenna
  - Broadband Antennas: Helical Antenna, Yagi-Uda Array
- Frequency Independent Antennas
  - Introduction
  - Theory
  - Frequency Independent Antennas: Equiangular Spiral, Log-Periodic Dipole Array

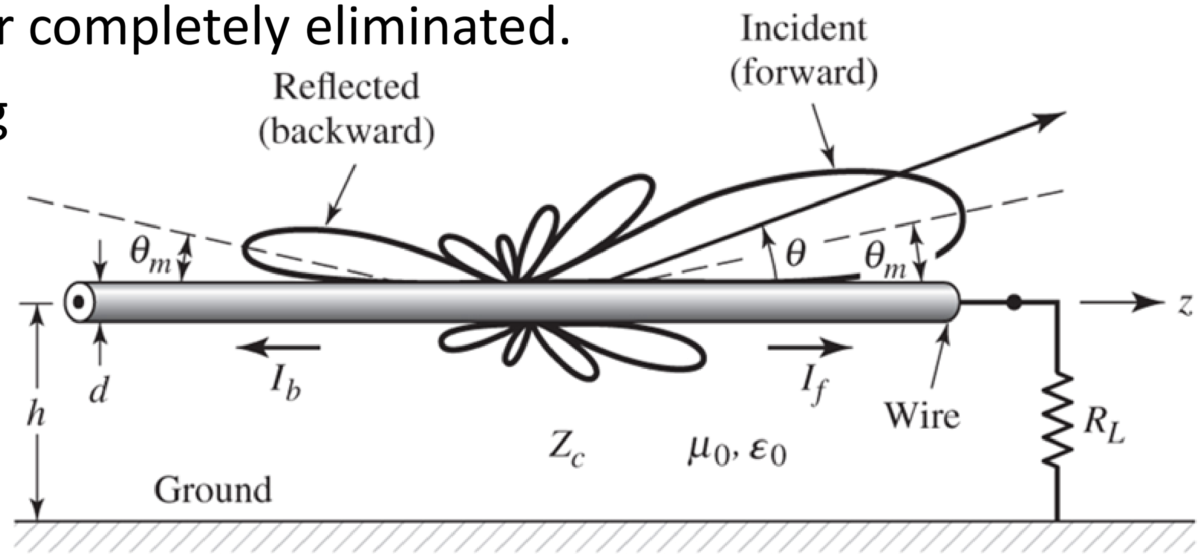
Traveling Wave Antennas

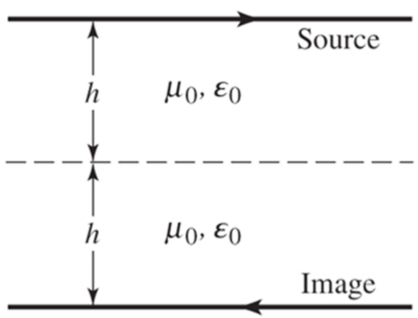
Traveling Wave Antennas- Introduction

So far the antennas we have discussed are **resonant**, **standing-wave** antennas. The maxima and minima from the patterns repeat every half integer wavelengths.

Antennas that have uniform patterns in current and voltage are **traveling wave, non-resonant** antennas. This can be achieved by properly terminating the antenna wire by properly terminating the antenna wire so that the reflections are minimized or completely eliminated.

An example of this traveling wave antenna is called the beverage antenna.





(a) Long wire above ground and radiation pattern

Chapter 10
Traveling Wave, Broadband Antennas

Traveling Wave Antennas- Introduction

A traveling wave can be classified as a slow wave if its phase velocity is equal or smaller than the speed of light, as opposed to fast waves, which the phase velocity is larger than the speed of light.

Traveling wave antennas can be classified in two types:

- Surface Wave Antenna: A slow wave structure that radiates power from discontinuities in the structure.
- Leaky-Wave Antenna: A fast wave structure that couples power from a traveling wave structure to free space

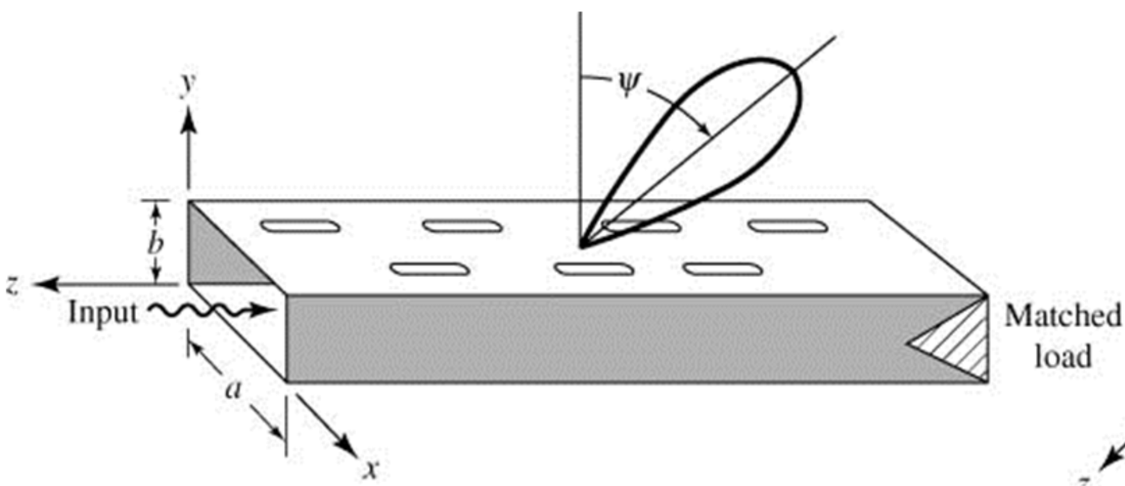


Fig. 10.2(a)

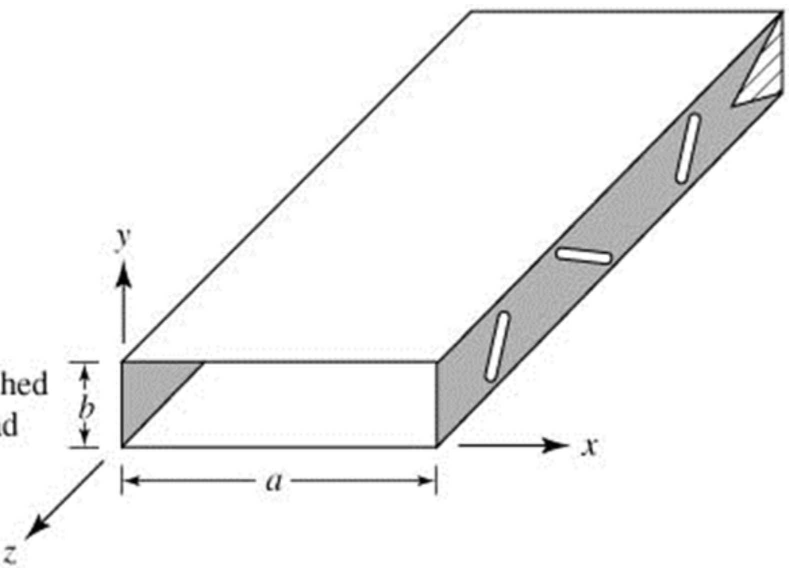


Fig. 10.2(b)

Long Wire (Beverage) Antenna

Invented in 1921 by H.H. Beverage. It is a straight conductor with a length from one to many wavelengths, above and parallel to the lossy earth. The height of the antenna must be chosen so that the reflected wave (wave from the image) is in phase with the direct wave.

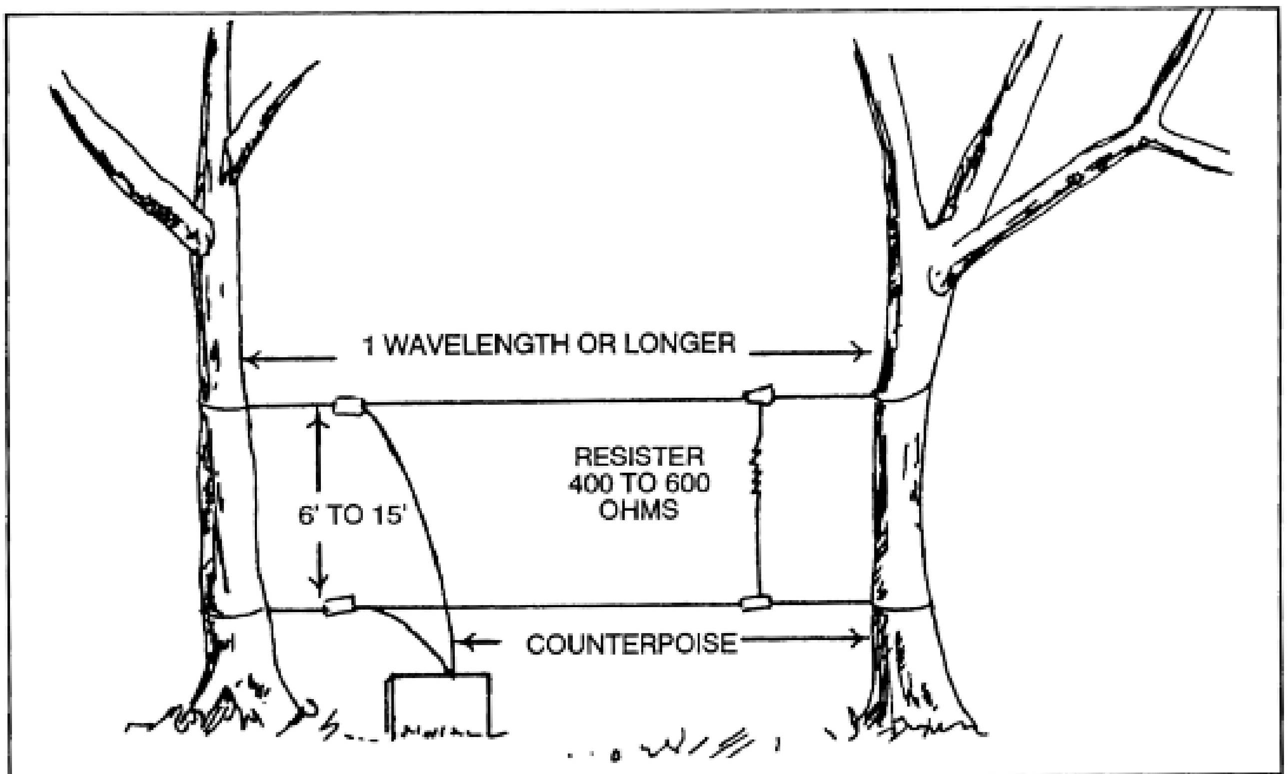
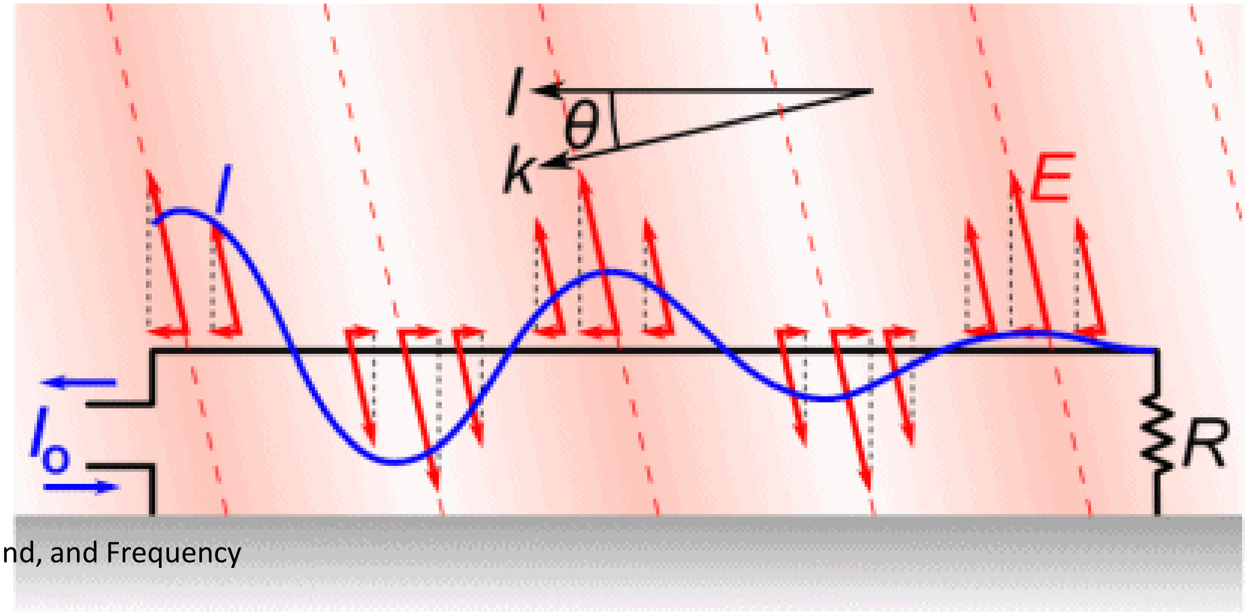


Figure D-11. Long-wire antenna.

Long Wire (Beverage) Antenna

It is primarily used as a directive receiving antenna because losses at load are big (inefficient).
The reception of the wave depends on the tilt arriving vertically. polarized caused by ground losses, and the input impedance is predominantly real.

$$R_L \cong 138 \log\left(4\frac{h}{d}\right)$$



Beverage Antenna - Radiation Pattern

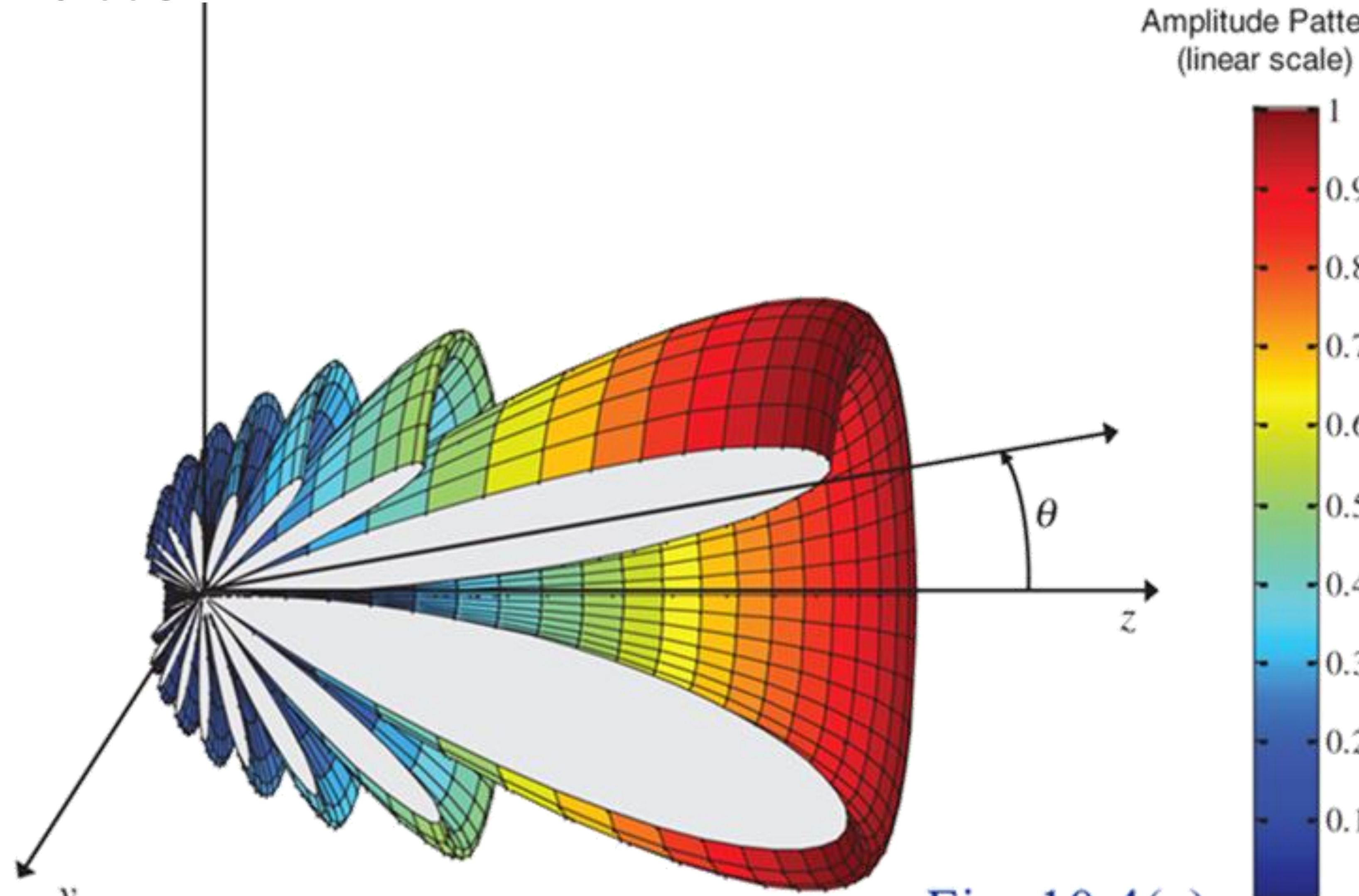
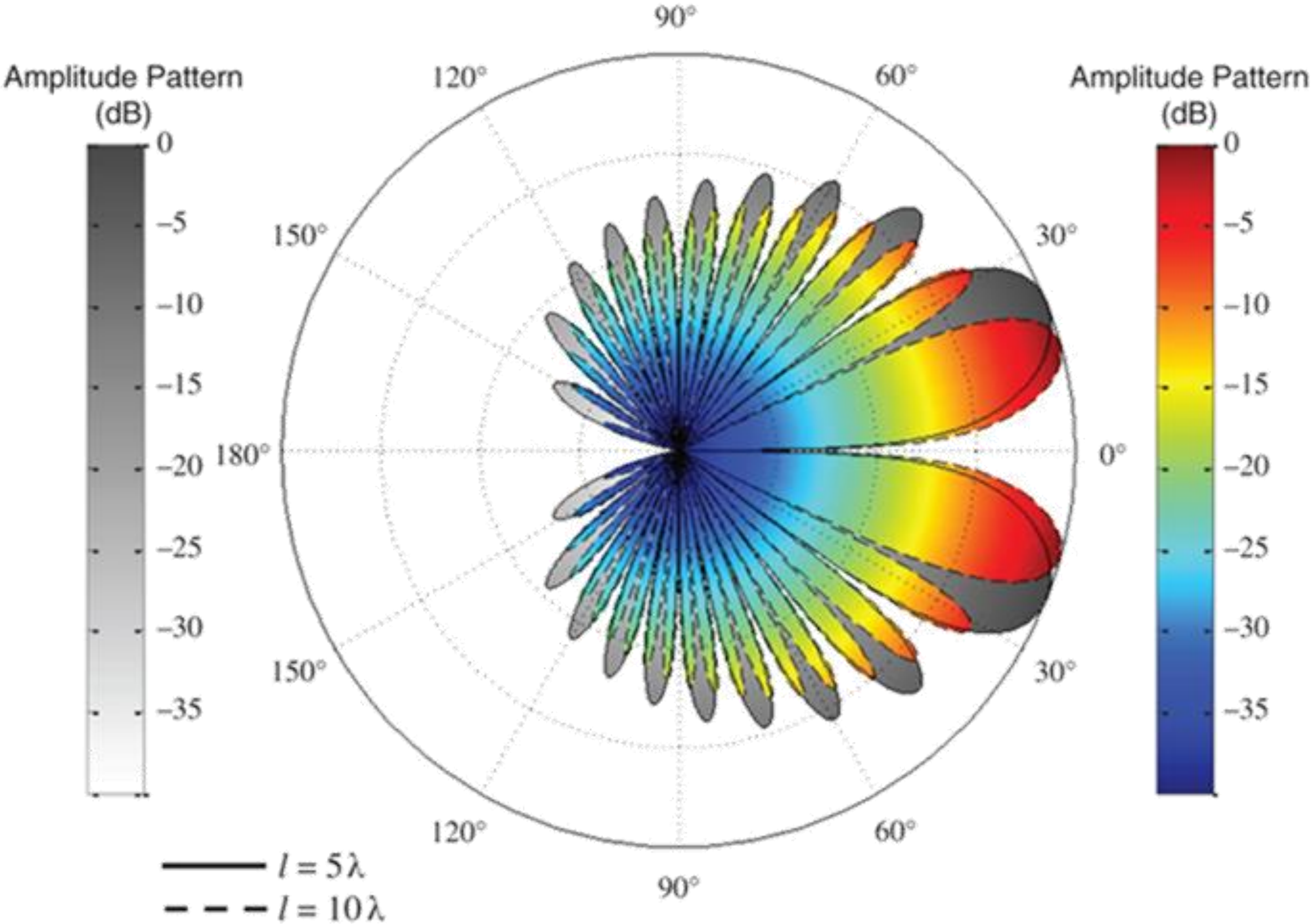


Fig. 10.4(a)

Beverage Antenna - Radiation Pattern



$l = 5\lambda$

$l = 10\lambda$

V Antenna

One very practical array of long wires is the symmetrical V antenna formed by using two wires with one of its ends connected to a feed line. By adjusting the angle, its directivity can be made greater and the side lobes smaller. The patterns of the individual wires of the V antenna are conical in form and inclined at an angle.

When the correct arrangements are made, the patterns are aligned and add constructively.

There is an optimum angle which leads to the largest directivity.

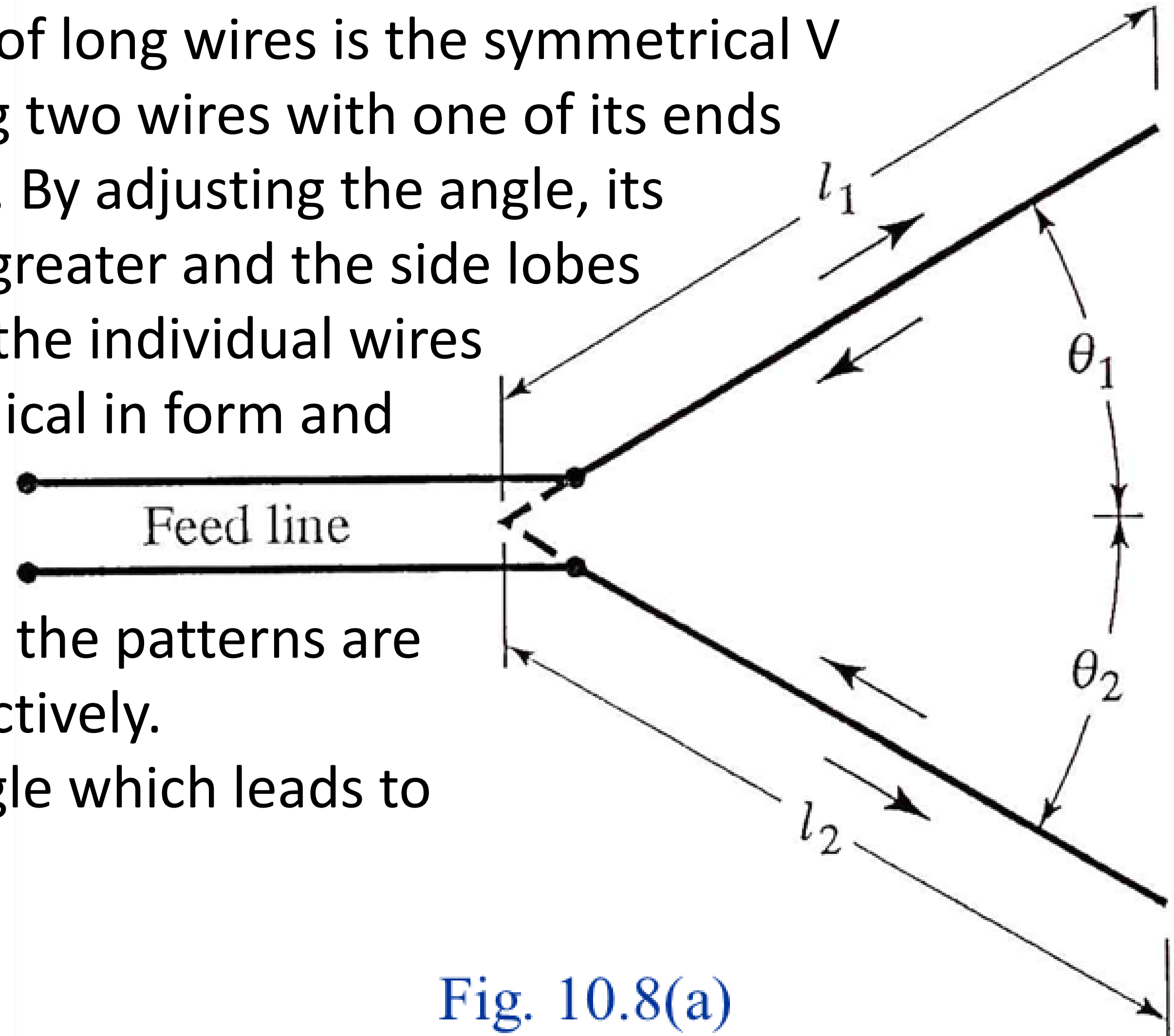
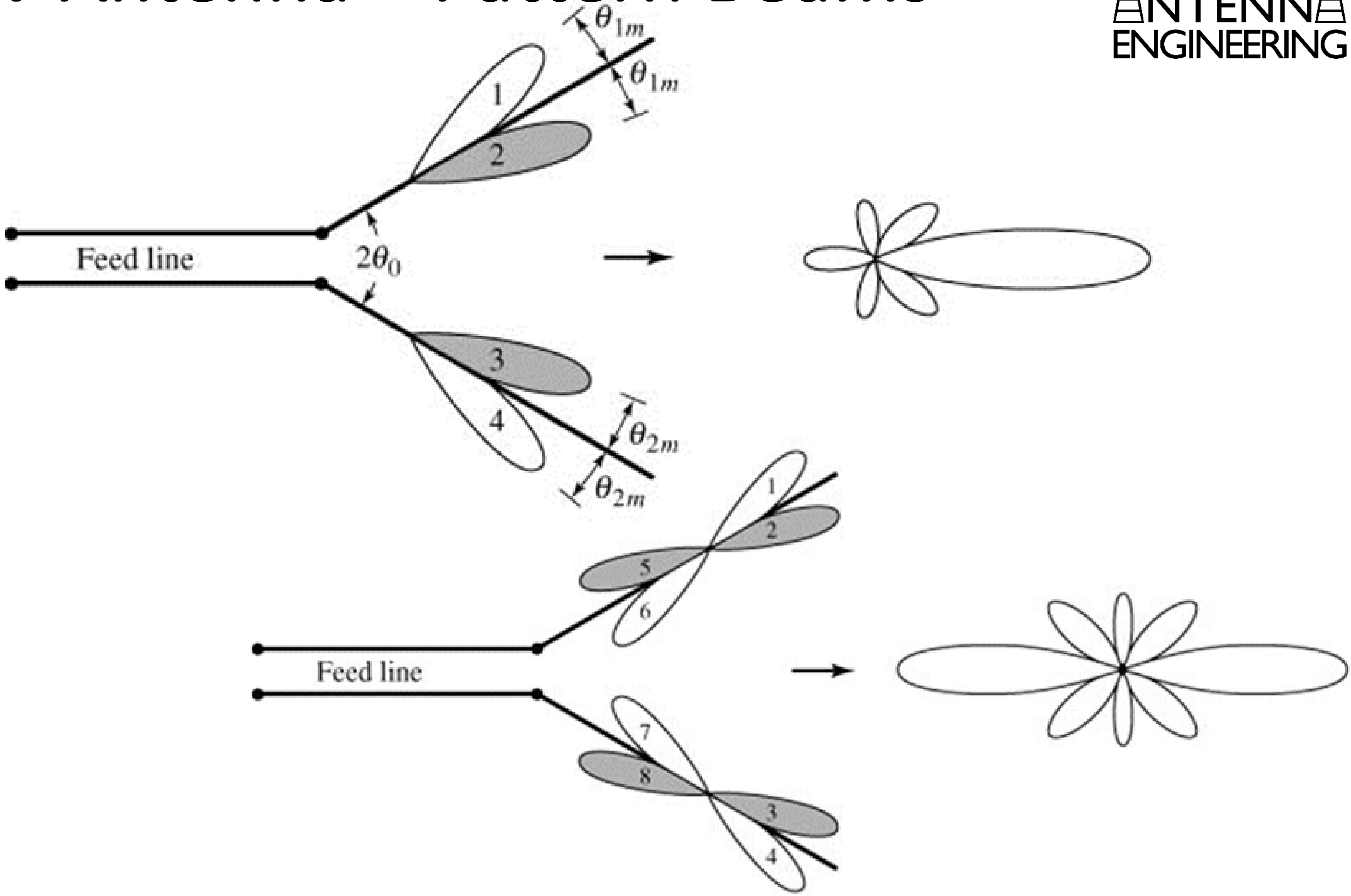


Fig. 10.8(a)

V Antenna – Pattern Beams



V Antenna – Parameters

Optimum angles for maximum directivity:

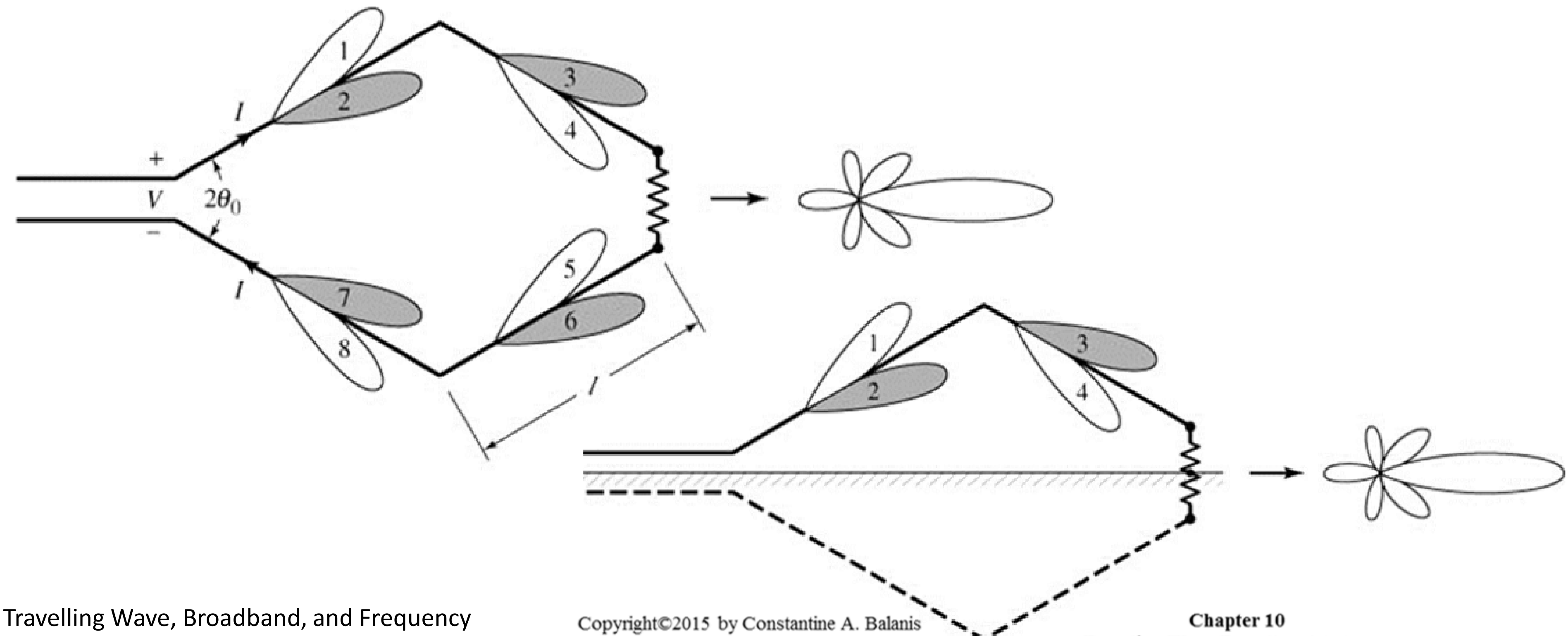
$$\boldsymbol{2\theta_0} = \begin{cases} -149.3\left(\frac{l}{\lambda}\right)^3 + 603.4\left(\frac{l}{\lambda}\right)^2 - 809.5\left(\frac{l}{\lambda}\right) + 443.6, & 0.5 \le \frac{l}{\lambda} \le 1.5 \\ 13.39\left(\frac{l}{\lambda}\right)^2 - 78.27\left(\frac{l}{\lambda}\right) + 169.77, & 1.5 \le \frac{l}{\lambda} \le 3 \end{cases}$$

Directivity of the antenna:

$$\boldsymbol{D_0} = 2.94\left(\frac{l}{\lambda}\right) + 1.15, \qquad 0.5 \le \frac{l}{\lambda} \le 3$$

Rhombic Antenna

The rhombic antenna are two V antennas connected in a diamond or rhombic shape, and terminated in the other end in a resistor to reduce or eliminate reflections.
If the length of the legs is large enough, a resistor may not be needed, and has high radiation efficiency.



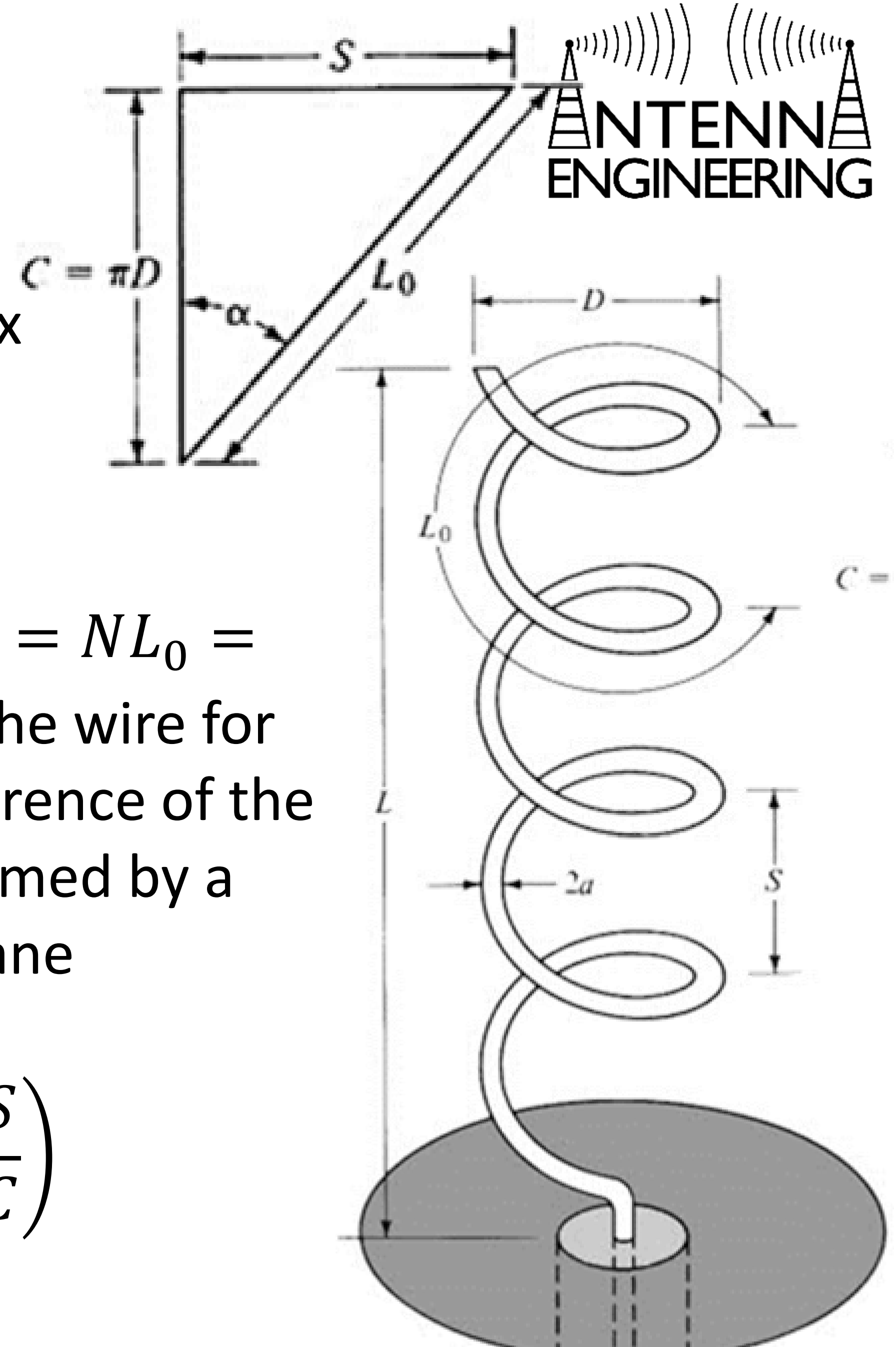
Chapter 10
Traveling Wave, Broadband Antennas

Broadband Antennas

Helical Antenna

The geometrical configuration of a helix consists usually of N turns, diameter D and spacing S between each turn. The total length of the antenna is $L = NS$ while the total length of the wire is $L_n = NL_0 = N\sqrt{S^2 + C^2}$ where L_0 is the length of the wire for each turn and $C = \pi D$ is the circumference of the helix. The pitch angle α is the angle formed by a line tangent for the helix wire and a plane perpendicular to the helix axis:

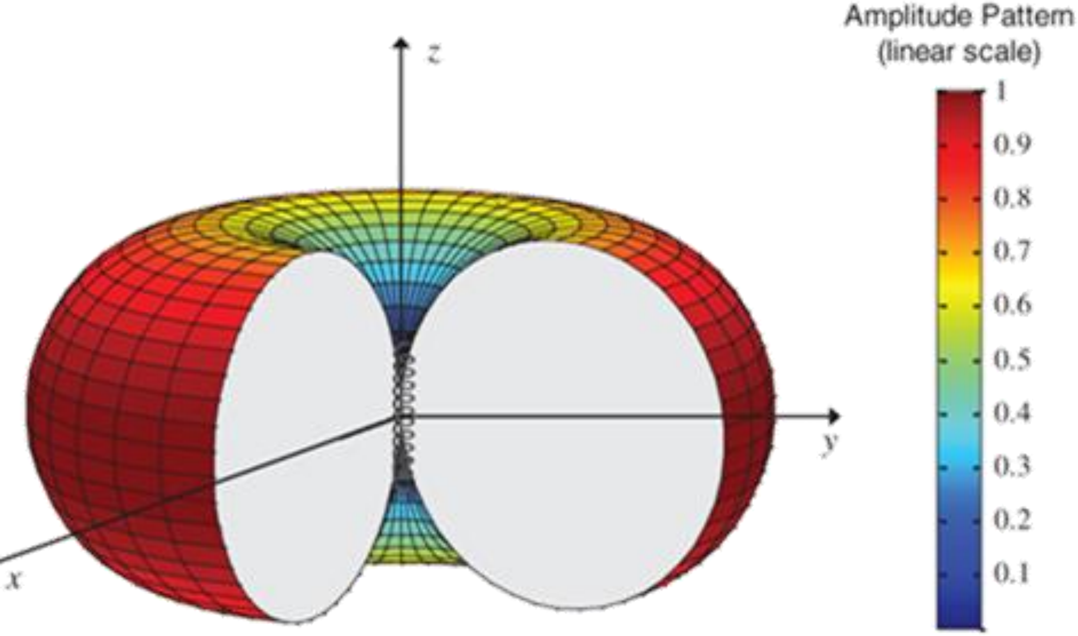
$$\alpha = \tan^{-1}\left(\frac{S}{\pi D}\right) = \tan^{-1}\left(\frac{S}{C}\right)$$



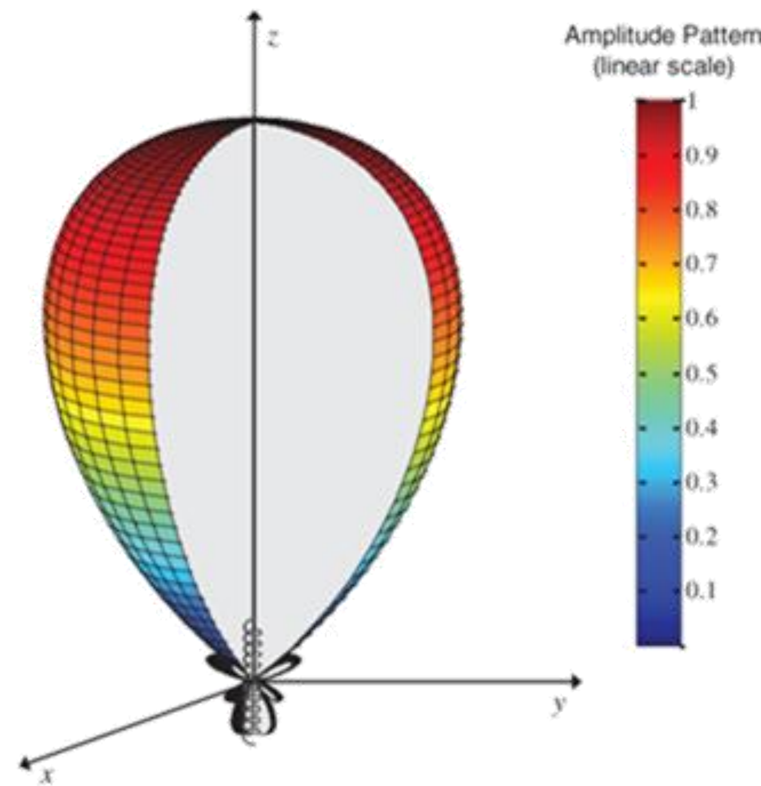
Chapter 10
Traveling Wave, Broadband Antennas

Helical Antenna

Normal Mode ($C<<\lambda$)



End-Fire Mode ($C\sim\lambda$)



Helical Antenna

The helical antenna operates in two principal modes:

Normal (broadside) mode

- Dimensions are small compared to wavelength $(NL_0 \ll \lambda_0)$
- The current throughout the antenna is assumed to be constant and its far-field independent of the number of loops and spacing.
- The fields radiate in θ and ϕ. The ratio between the magnitudes of these fields is defined as the axial ratio:

$$AR = \frac{|E_\theta|}{|E_\phi|} = \frac{4S}{\pi k D^2} = \frac{2\lambda S}{(\pi D)^2}$$

$$AR = 0 \ - \text{Horizontal Polarization}$$
$$AR = \infty \ - \text{Vertical Polarization}$$
$$AR = 1 \ - \text{Circular Polarization} \left(\mathrm{C} = \pi D = \sqrt{2S\lambda_0}, \tan\alpha = \frac{\pi D}{2\lambda_0} \right)$$
$$\text{Other values of } AR \ - \text{Elliptical Polarization}$$

Helical Antenna

The helical antenna operates in two principal modes:

Axial (end-fire) mode

- To achieve circular polarization, the circumference must be $\frac{3}{4} \leq \frac{C}{\lambda_0} \leq \frac{4}{3}$, and spacing about $S \cong \frac{\lambda_0}{4}$, pitch angle $12^{\circ} \leq \alpha \leq 14^{\circ}, \mathrm{N} > 3$.
- Input Resistance is around

$$R \cong 140\left(\frac{C}{\lambda_0}\right)$$

- Half-Power Beamwidth is around

$$\mathrm{HPBW(degrees)} = \frac{52\lambda_0^{3/2}}{C\sqrt{NS}}$$

- Axial Ratio to achieve increased directivity

$$AR = \frac{2N+1}{2N}$$

- Directivity is given by

$$D_0(\mathrm{dimensionless}) = 15\mathrm{N}\frac{C^2 S}{\lambda_0^3}$$

Helical Antenna - Example

Design a 10-turn helix to operate in the axial mode.

Determine

a) The circumference in wavelengths, the pitch angle in degrees, and separation between turns (in wavelengths)
b) HPBW of the main lobe in degrees
c) Directivity in dB

Helical Antenna - Example

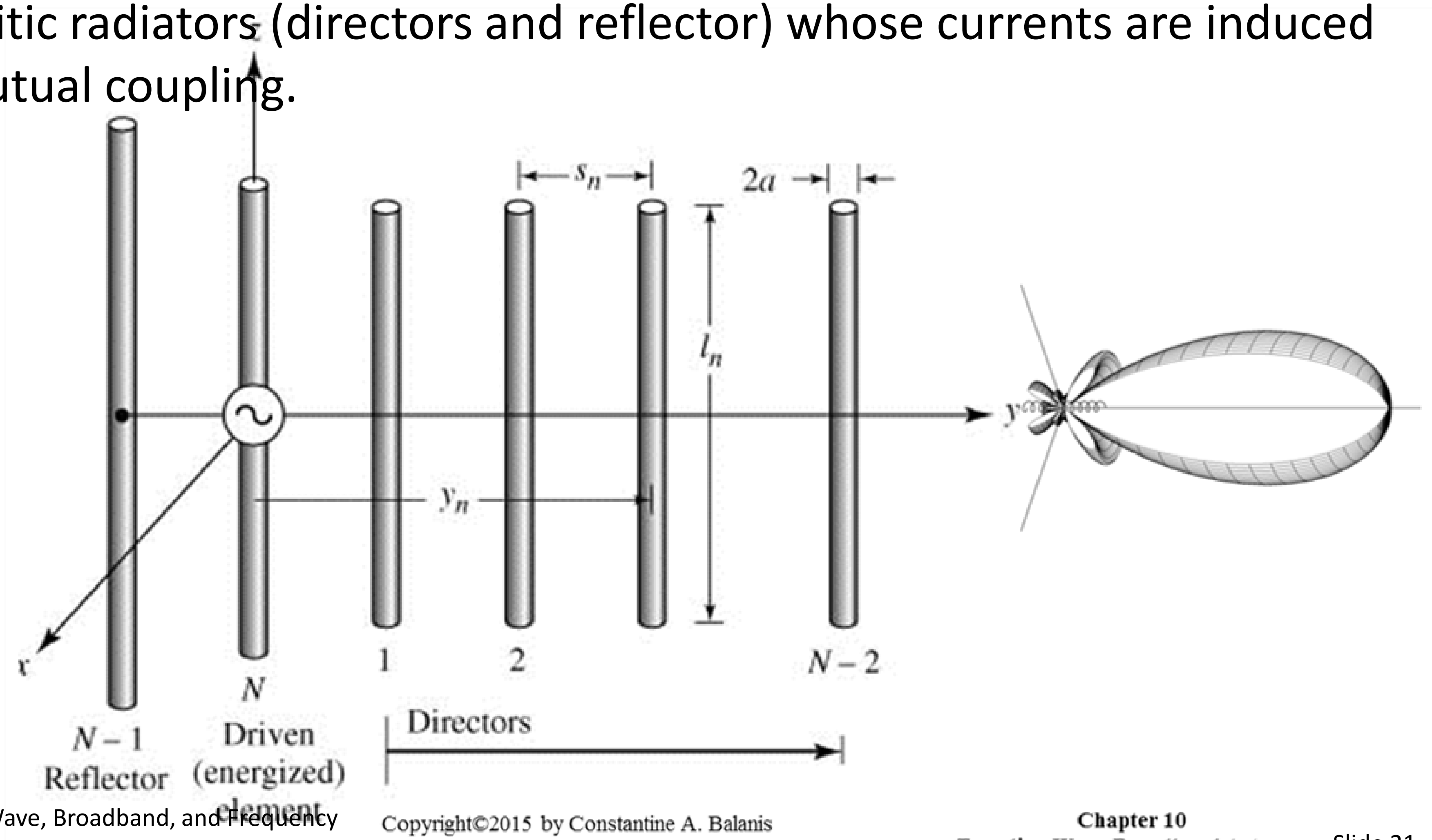
Design a 5-turn helical antenna at $400\ \mathrm{MHz}$ to operate in the normal mode. The spacing between turns is $\lambda_0/50$. It is desired that the antenna possesses circular polarization.

Determine

a) The circumference of the helix in meters
b) Length of a single turn in meters
c) Length of the entire helix in meters
d) Pitch angle in degrees

Yagi-Uda Array of Linear Elements

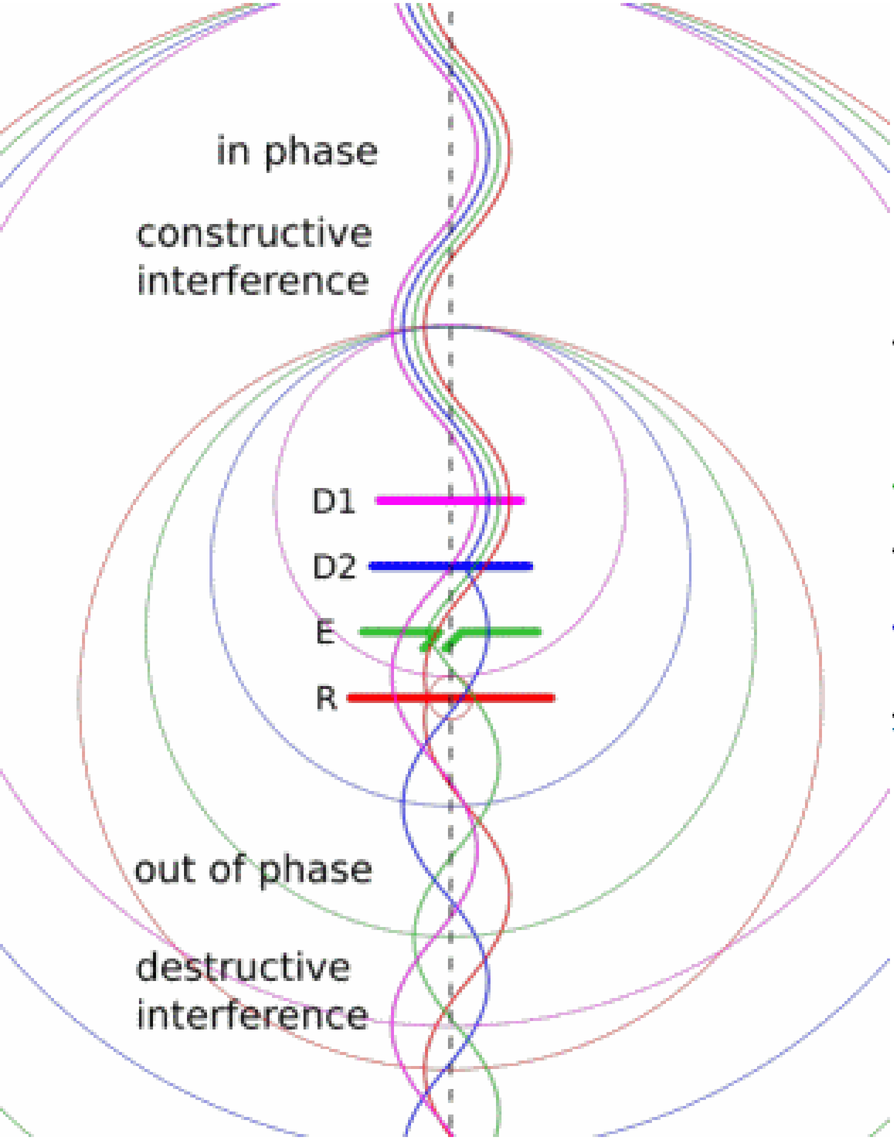
An array consisting of a number of linear dipole elements. One of them is energized directly by a feed transmission line while the others act as parasitic radiators (directors and reflector) whose currents are induced by mutual coupling.

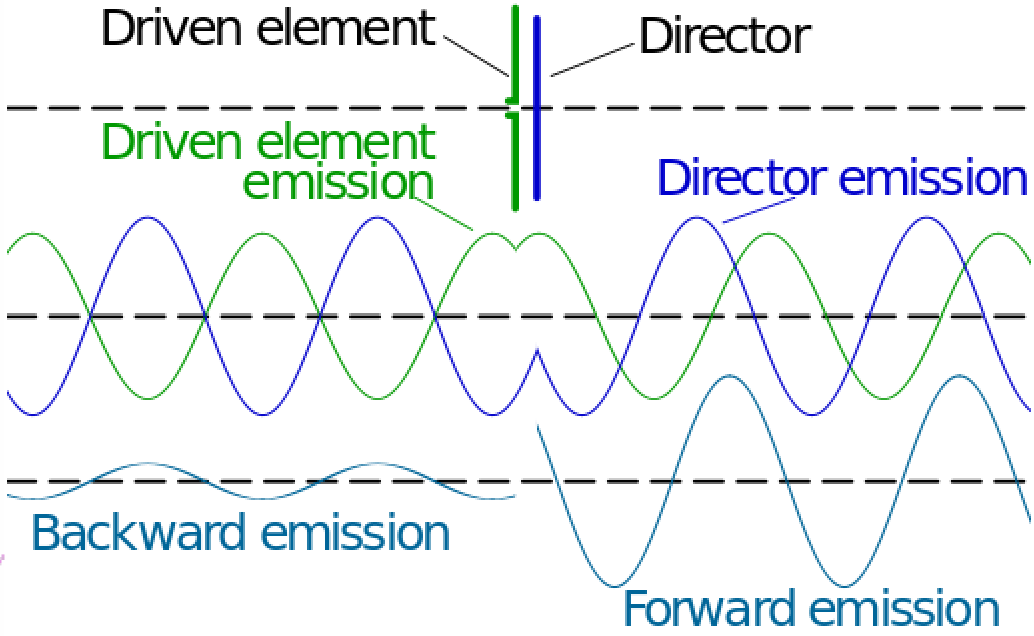


Yagi-Uda Array of Linear Elements

Yagi-Uda Arrays are quite common in practice because they are lightweight, simple to build, low-cost, and provide moderately desirable characteristics for many applications (e.g. Cable TV, Military)

Yagi-Uda Array of Linear Elements





Frequency Independent Antennas

Frequency Independent Antennas - Introduction

In the 1950s, there was a breakthrough in antenna evolution that drove antenna designs to a bandwidth as great as 40:1 or even more. These antennas have a variety of practical applications such as TV, point-to-point communication, feeds for reflectors and lenses, etc.

One of the characteristics is EM scaling: if all physical dimensions of a device are reduced by a factor of 2, the performance of the antenna will remain unchanged if the frequency is increased by a factor of 2. Based on the same principle, if the shape of the antenna were completely specified by angles, the performance would be independent of frequency.

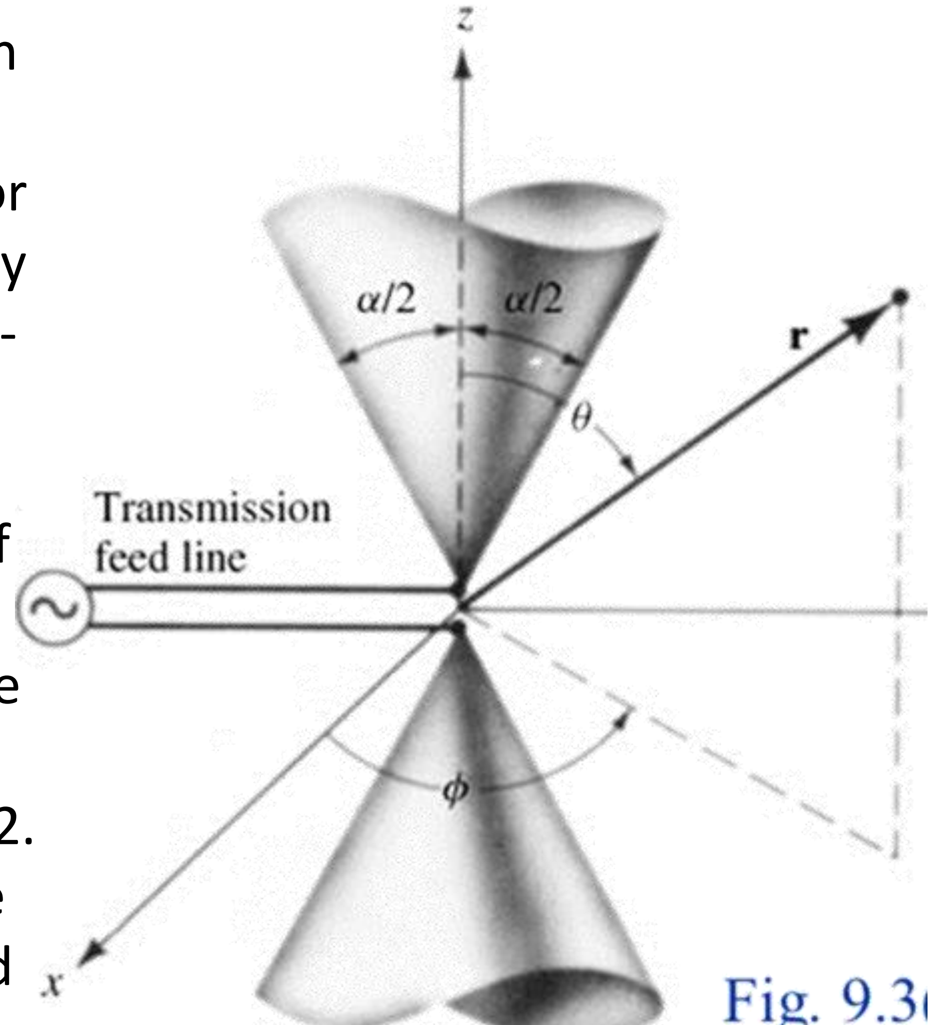


Fig. 9.3

Frequency Independent Antennas - Theory

Assumptions: antenna is described in spherical coordinates, both terminals are placed infinitely close to the origin, and placed at $\theta = 0, \pi$, the antenna is perfectly conducting, infinitely surrounded by homogeneous and isotropic medium, and its surface or an edge on its surface is described by

$$r = F(\theta, \phi)$$

Where r is the distance along the surface or edge. If the antenna is to be scaled to a frequency K times lower the original frequency, the antenna must be K times greater to maintain the same electrical dimensions:

$$r' = KF(\theta, \phi)$$

New and old surfaces are identical geometrically, means that they're congruent by rotating only in ϕ:

$$KF(\theta, \phi) = F(\theta, \phi + C)$$

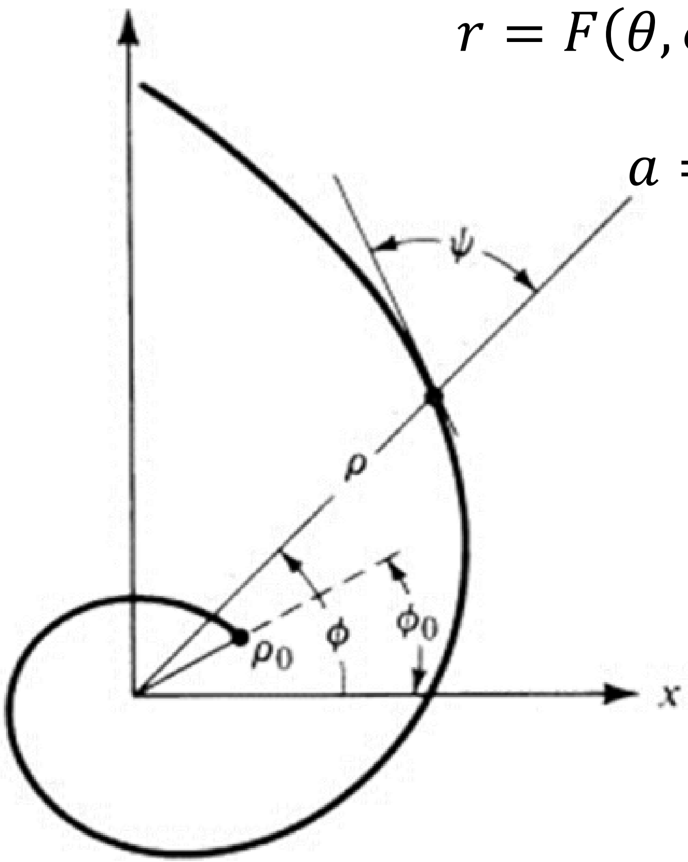
where the angle of rotation C only depends on K.

Frequency Independent Antennas - Theory

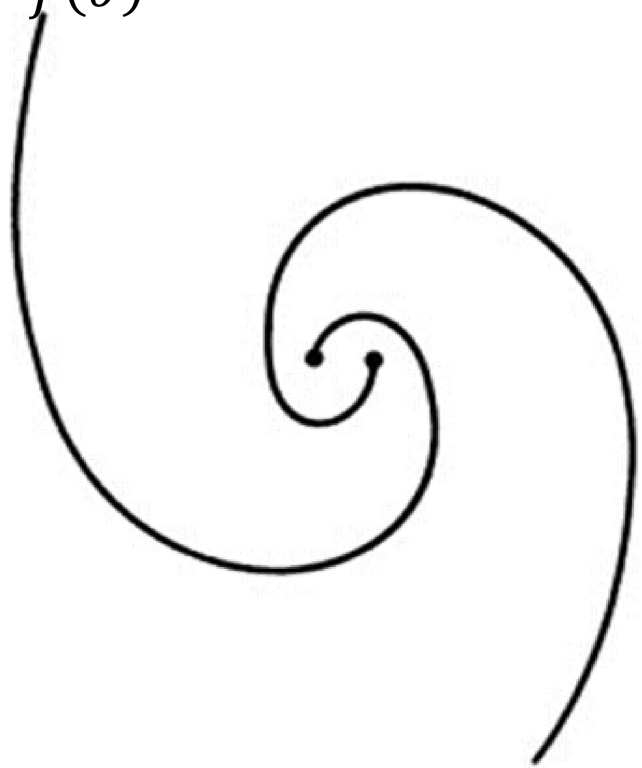
For the antenna to be independent of frequency its surface, and independent of θ and ϕ, it must be described by

$$r = F(\theta, \phi) = e^{a\phi} f(\theta)$$

$$a = \frac{1}{K}\frac{dK}{dC}$$



(a) Single Spiral



(b) Two Spirals ($\phi_0 = 0, \pi$)

Equiangular Spiral Antenna

The geometry of the spiral antenna can be described by

$$r\Big|_{\theta=\pi/2} = \rho = \begin{cases} Ae^{a\phi} = \rho_0 e^{a(\phi-\phi_0)}, \theta = \pi/2 \\ 0, \qquad \text{elsewhere} \end{cases}$$

$$A = \rho_0 e^{-a\phi_0}$$

Another form of the equation is

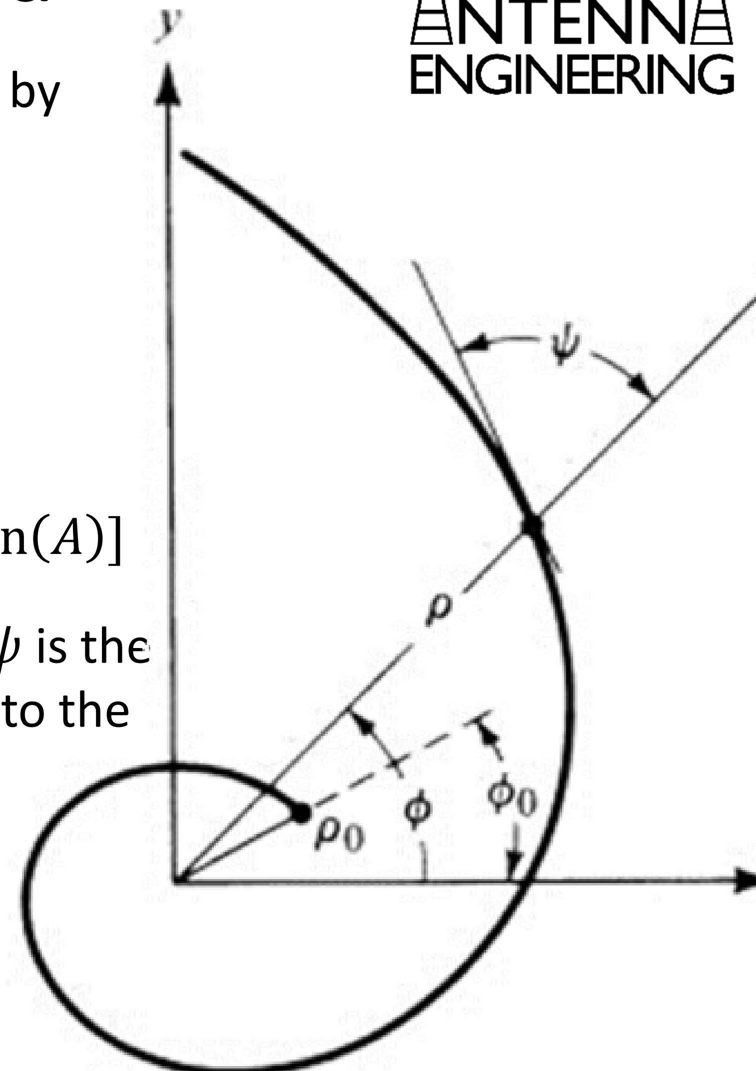
$$\phi = \frac{1}{a}\ln\left(\frac{\rho}{a}\right) = \tan(\psi)\ln\left(\frac{\rho}{A}\right) = \tan(\psi)\left[\ln(\rho) - \ln(A)\right]$$

where $1/a$ is the rate of expansion of the spiral and ψ is the angle between the radial distance ρ and the tangent to the spiral.

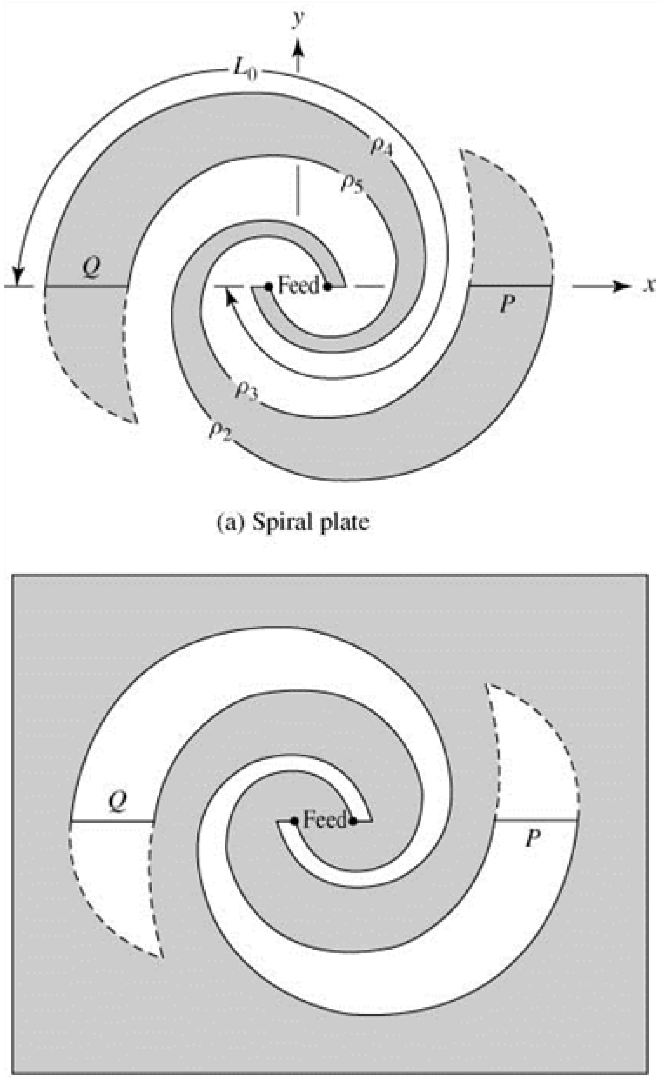
The length of the antenna is given by

$$L = (\rho_1 - \rho_0)\sqrt{1 + \frac{1}{a^2}}$$

Where ρ_0 and ρ_1 represent the inner and outer radii of the spiral.



Equiangular Spiral Antenna



(a) Spiral plate

(b) Spiral slot

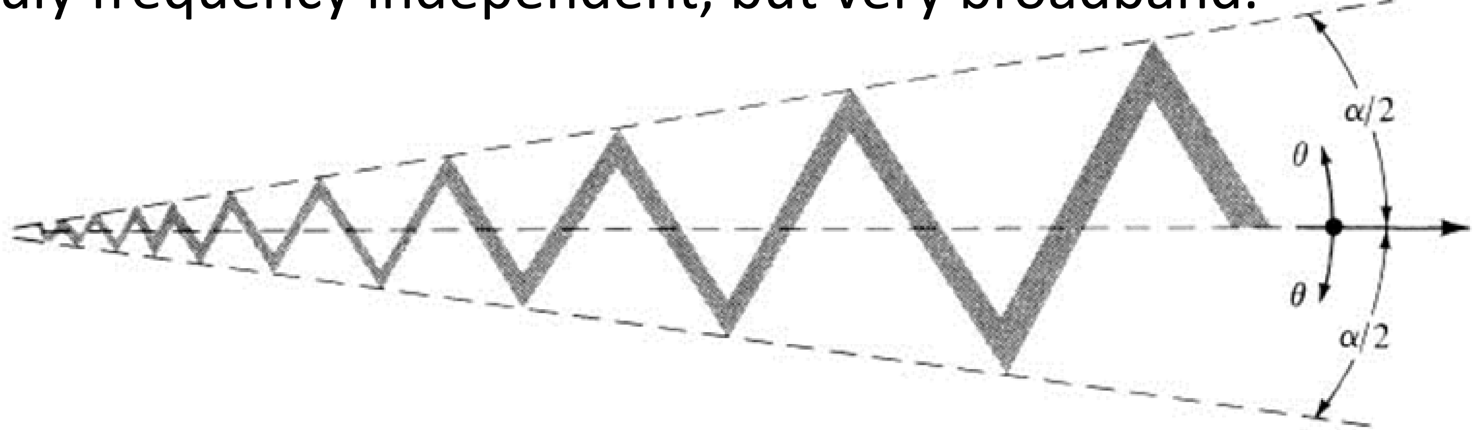
As stated before, the geometry of the antenna is described by angles. The lowest frequency of operation occurs when the total arm length is comparable to one wavelength.
For all frequencies above this, the pattern and impedance are frequency independent. For a phase angle change of $\pi/2$,

$$Z_0 = 188.5 \cong 60\pi\ \Omega$$

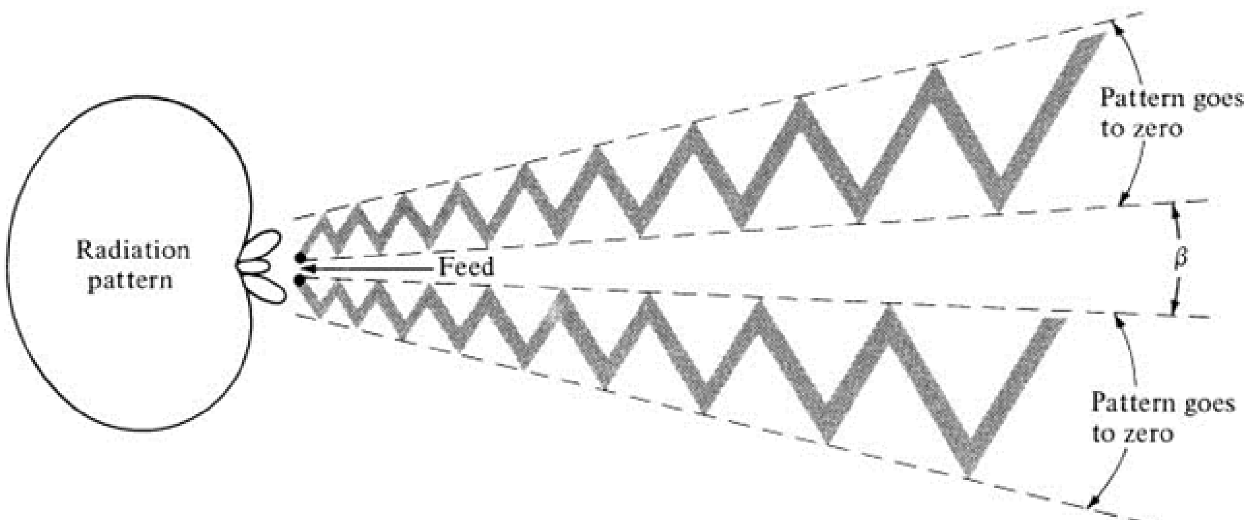
Although in practice the measurements are lower ($164\ \Omega$), attributed to the finite arm length, finite thickness of the plate, and non-ideal feeding conditions.

Log-Periodic Antenna

Not truly frequency independent, but very broadband.



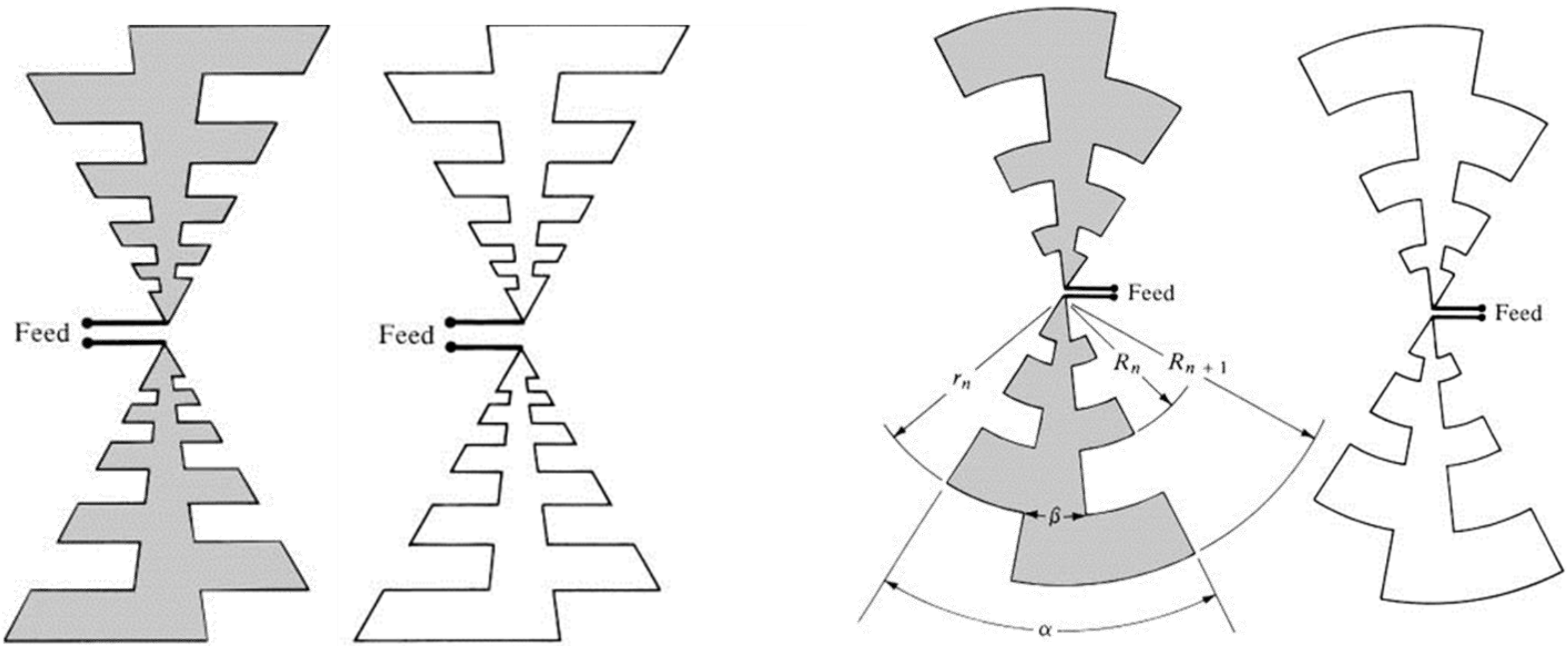
(a) Metal Strip Log-Periodic Configuration



(b) Log-Periodic Metal Strip Antenna

Log-Periodic Antenna

The removal of the inner surface of the antenna does not significantly impact the radiation characteristics.



Log-Periodic Antenna

Geometric Ratio τ (defines period):

$$\tau = \frac{R_n}{R_{n+1}} < 1 \qquad (11\text{-}23)$$

Width of Slot:

$$\chi = \frac{r_n}{R_{n+1}} < 1 \qquad (11\text{-}24)$$

$$\tau = \frac{f_1}{f_2} < 1,\ f_2 > f_1 \qquad (11\text{-}25)$$

f_1 and f_2 are one period apart.

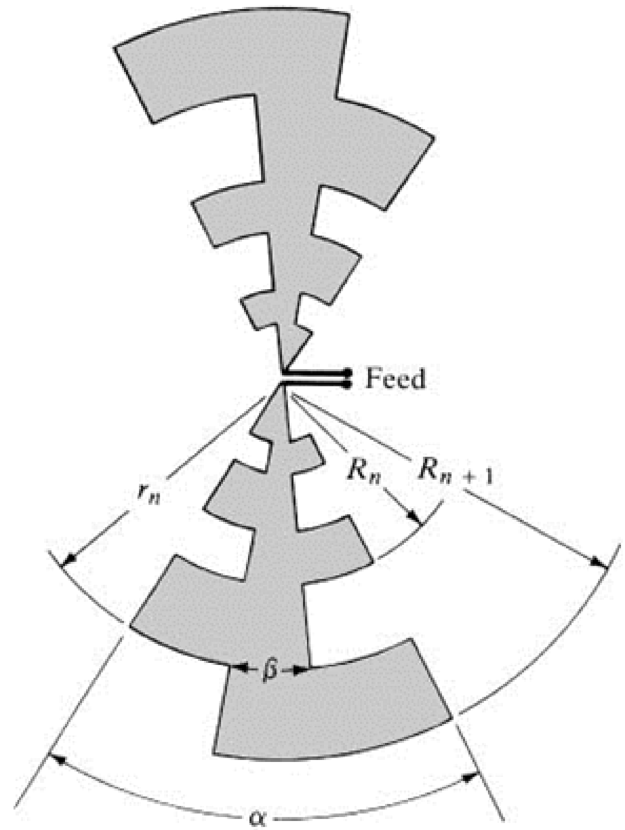
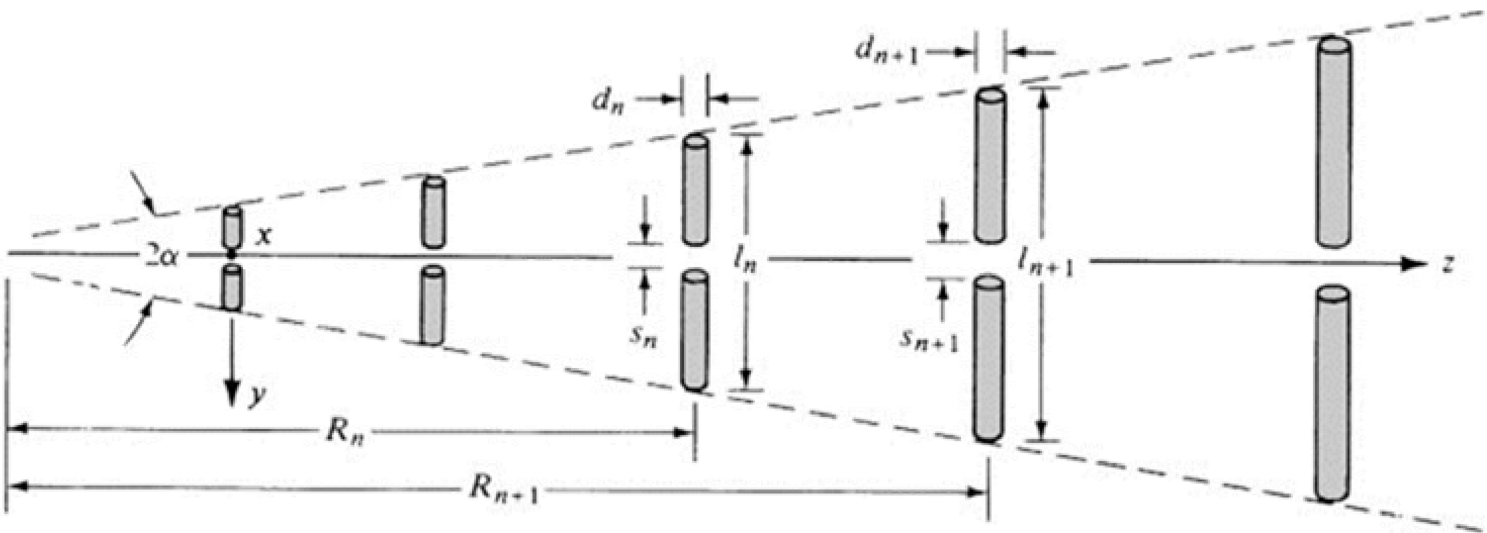


Fig. 11.6(a)

Log-Periodic Dipole Array

1. The Log-Periodic Dipole Array (LPDA) is the most commonly used VHF antenna for TV that supports all channels
2. It is capable of constant gain and input impedance over a bandwidth of 30:1
3. Has a gain range from 6.5-10.5 dB for half-wave dipole
4. The dipoles are connected to a central transmission line with phase reversal between dipoles, so that radiation is back-fire



Chapter 11
Frequency Independent Antennas, Antenna Miniaturization

Log-Periodic Dipole Array

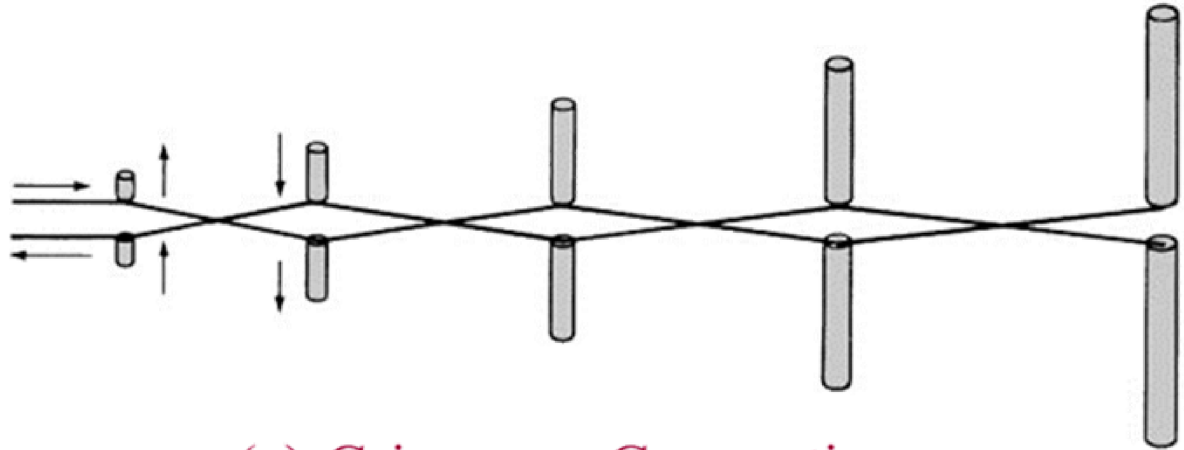
$$\frac{1}{\tau} = \frac{\ell_2}{\ell_1} = \frac{\ell_{n+1}}{\ell_n} = \frac{R_2}{R_1} = \frac{R_{n+1}}{R_n}$$

$$= \frac{d_2}{d_1} = \frac{d_{n+1}}{d_n} = \frac{s_2}{s_1} = \frac{s_{n+1}}{s_n} \qquad (11\text{-}26)$$

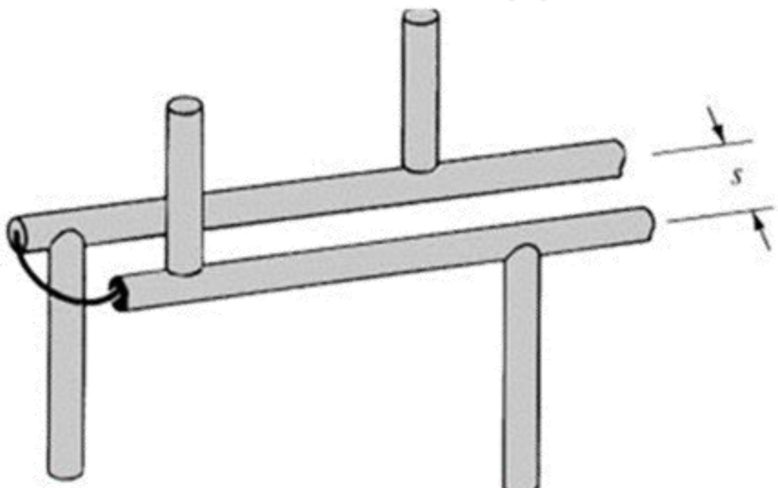
Spacing Factor σ:

$$\sigma = \frac{R_{n+1} - R_n}{2\ell_{n+1}} \qquad (11\text{-}26a)$$

Log-Periodic Dipole Array

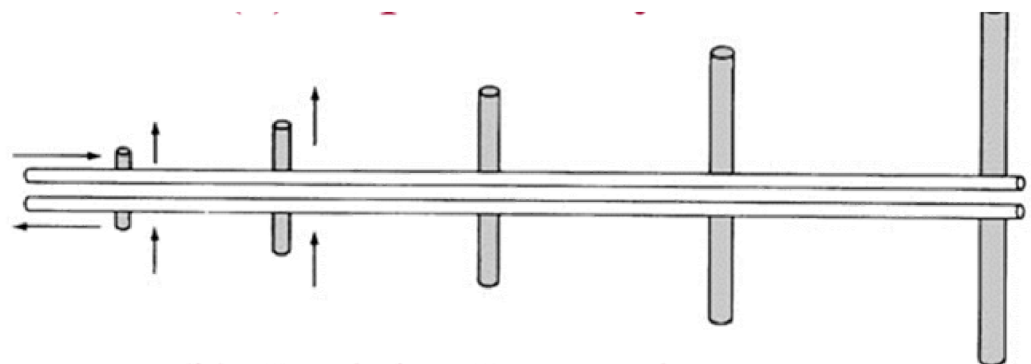


(c) Crisscross Connection



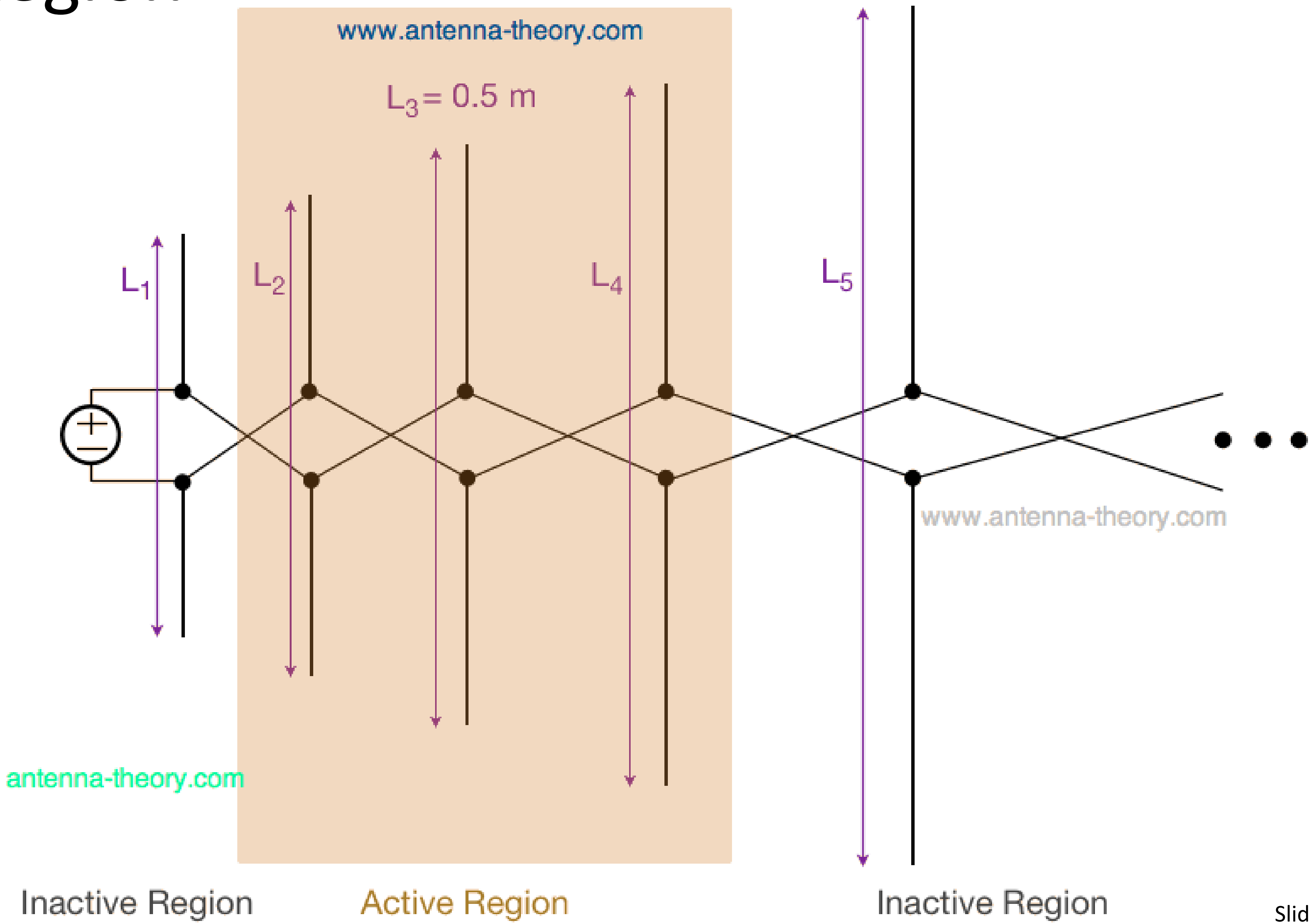
(d) Coaxial Connection

Fig

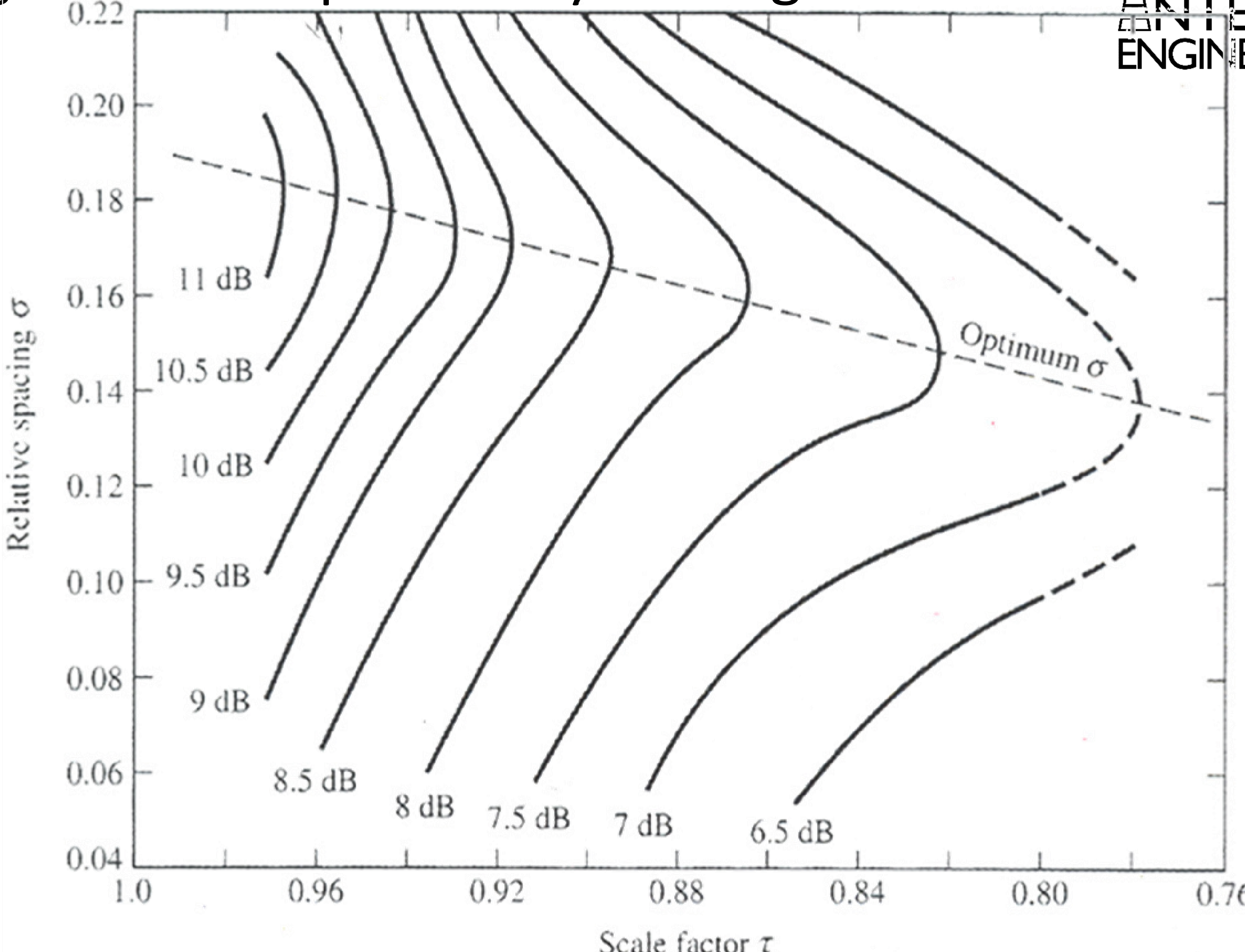


(b) Straight Connection

Log-Periodic Dipole Array – Active Region



Log-Periodic Dipole Array – Design Procedure



Log-Periodic Dipole Array – Design Procedure

Aperture angle:

$$\alpha = \tan^{-1}\left[\frac{1-\tau}{4\sigma}\right]$$

Bandwidth of the active region:

$$B_{ar} = 1.1 + 7.7(1-\tau)^2 \cot(\alpha)$$

A more ‘practical’ bandwidth (B is in fractional form):

$$B_s = BB_{ar}$$
$$B_s = designed\ bandwidth$$
$$B = desired\ bandwidth$$

The total length of the structure is

$$L = \frac{\lambda_{max}}{4}\left(1 - \frac{1}{B_s}\right)\cot(\alpha)$$

Where

$$\lambda_{max} = 2l_{max} = \frac{c_0}{f_{min}}$$

Log-Periodic Dipole Array – Design Procedure

The number of elements is determined by

$$N = 1 + \frac{\ln(B_s)}{\ln\left(\frac{1}{\tau}\right)}$$

The average characteristic impedance of the elements is given by

$$Z_a = 120\left[\ln\left(\frac{l_n}{d_n}\right) - 2.25\right]$$

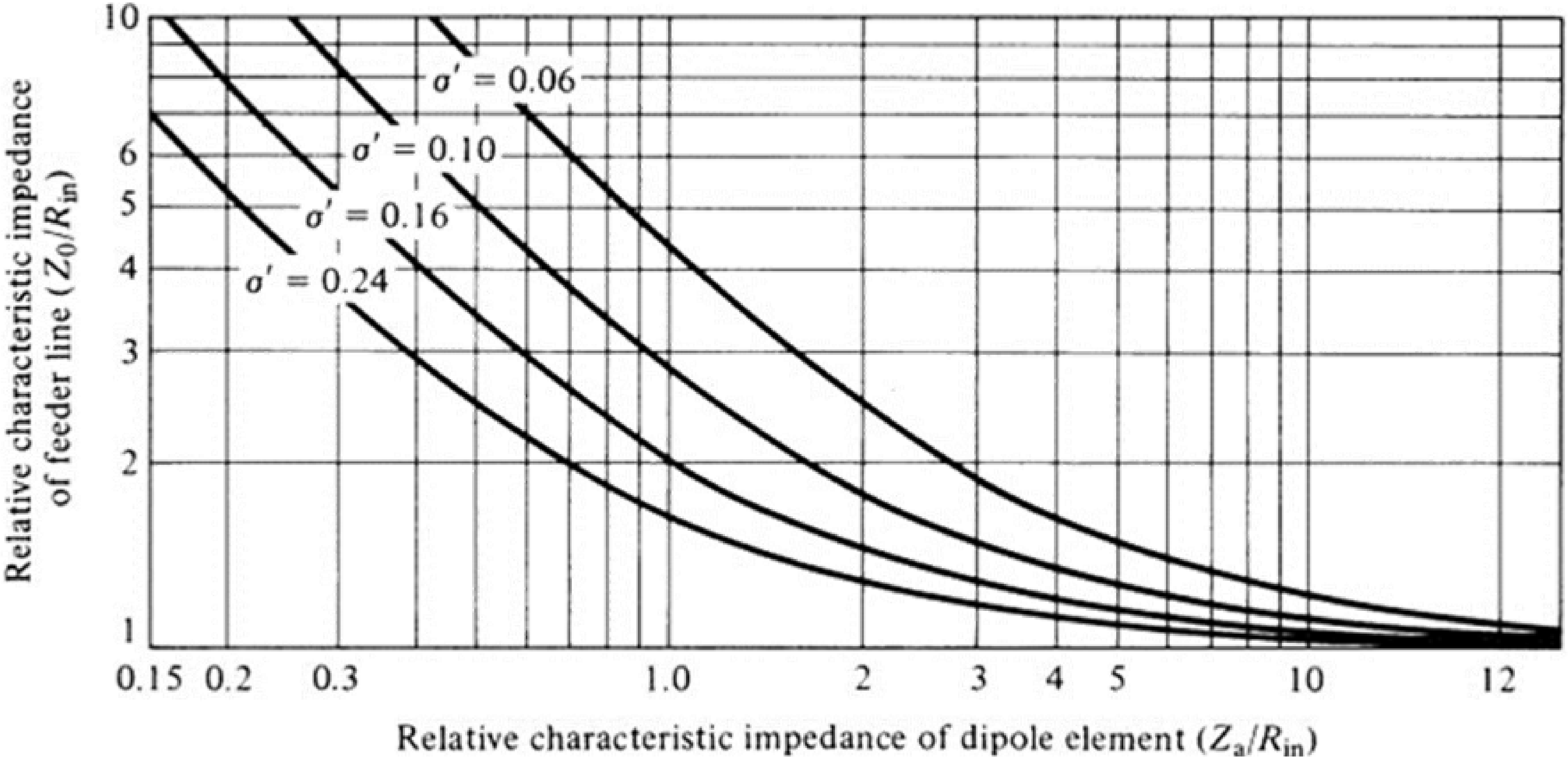
The relative mean spacing between elements is

$$\sigma' = \sigma/\sqrt{\tau}$$

The center-to-center spacing between the two rods of the feeder line is

$$s = d\cosh\left(\frac{Z_0}{120}\right)$$

Log-Periodic Dipole Array – Design Procedure



Log-Periodic Dipole Array - Example

Design a log-periodic dipole antenna, to cover all VHF channels (54 MHz for Channel 2 to 216 MHz for Channel 13). The desired directivity is 8 dB and the input impedance needs to be matched to a $50\ \Omega$ coaxial cable. The antenna elements are made of aluminum tubing $3/4$ in. (1.9 cm) for the largest element and the feeder line and $3/16$ in. (0.48 cm) for the smallest element. These diameters yield identical l/d ratios for the smallest and largest elements.