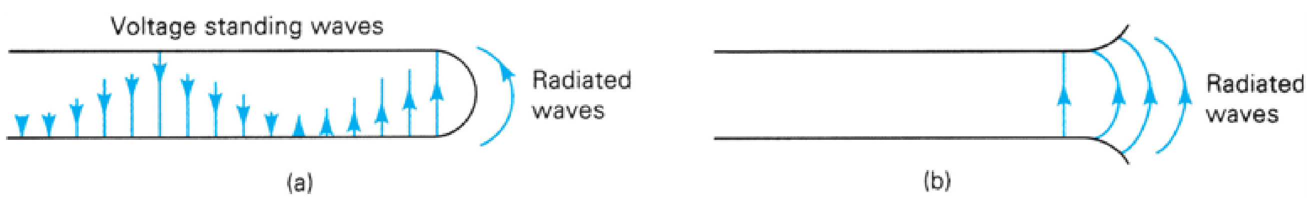
Antenna Theory

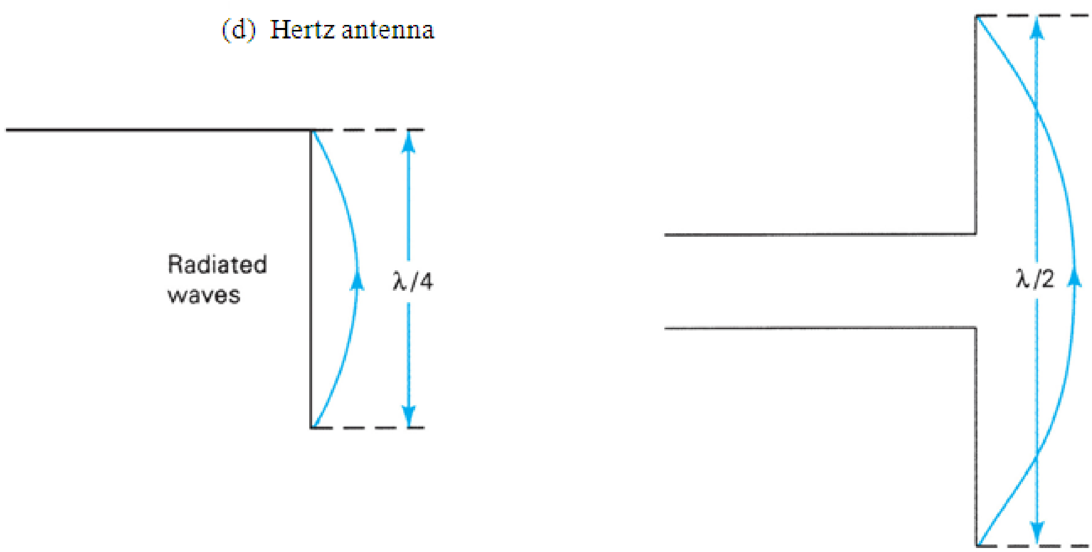
ANTENNA

- Consists of a wire or other conductor, or a collection of wires or conductors, that converts electrical energy into electromagnetic waves for transmission, and electromagnetic waves into electrical energy for reception
- An antenna passive reciprocal device.
- Acts as a transducer to convert electrical oscillations in a transmission line or waveguide to a propagating wave in free space and vice versa.
- Functions as an impedance matcher between a transmission line or waveguide and free space.
- All antennas have a radiation pattern which is a plot of the field strength or power density at various angular positions relative to the antenna.

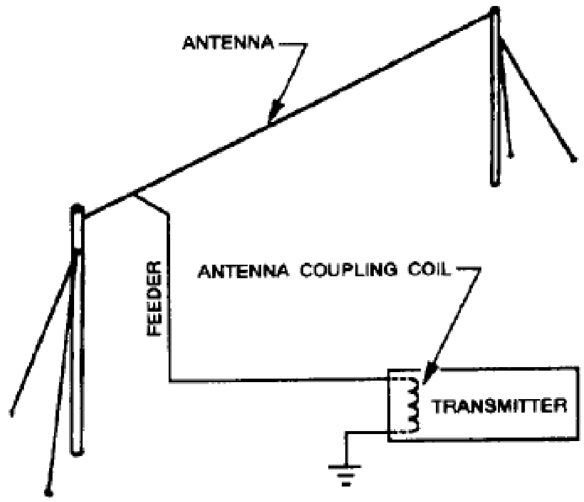
Basic Antenna Operation



Radiation from a transmission line: (a) transmission-line radiation; (b) spreading conductors; (c) Marconi antenna; (d) Hertz antenna



Complete Antenna System



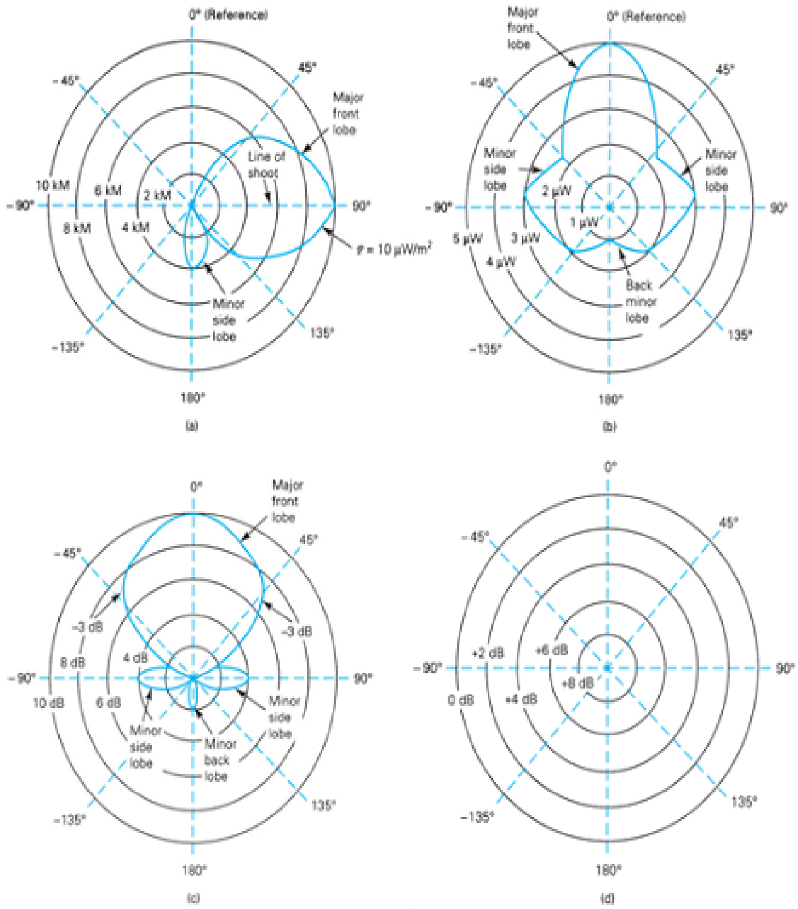
The coupling device (coupling coil) connects the transmitter to the feeder. The feeder is a transmission line that carries energy to the antenna. The antenna radiates this energy into space.

Antenna Terminology and Parameters

Radiation Pattern – a polar diagram or graph representing field strengths or power densities at various angular positions relative to an antenna.

Absolute radiation pattern - radiation pattern plotted in variable distance, fixed power
Relative radiation pattern - radiation pattern plotted in variable power, fixed distance
Front lobe – major lobe; lobe that receives the most energy
Side lobes – lobes adjacent to the front lobe
Back lobes – lobes in direction exactly opposite the front lobe

Radiation patterns: (a) absolute (fixed power) radiation pattern; (b) relative (fixed distance) radiation pattern; (c) relative (fixed distance) radiation pattern in decibels; and (d) relative (fixed distance) radiation pattern in decibels for an omnidirectional (point source) antenna



Front-to-back ratio – ratio of the front lobe power to the back lobe power
Front-to-side ratio - ratio of the front lobe power to the side lobe power
Line of shoot or point of shoot – line bisecting the major lobe from the center of the antenna in the direction of maximum radiation

Near field – field pattern that is close to the antenna (induction field)
Far field - field pattern that is at a great distance (radiation field)

During one-half of a cycle, power is radiated from an antenna where some of the power is stored temporary in the near field. During the second half of the cycle, power in the near field is returned to the antenna.

Radiation resistance – the resistance that, if it replaced the antenna, would dissipate exactly the same amount of power that the antenna radiates

$$R_r = \frac{P}{i^2}$$

Antenna efficiency – ratio of the power radiated by an antenna to the sum of the power radiated and the power dissipated

$$\eta = \frac{P_{rad}}{P_{in}} = \frac{P_{rad}}{P_{rad} + P_d} = \frac{R_r}{R_r + R_e}$$

Where: η = antenna efficiency
P_{rad} = power radiated by an antenna (W)
P_d = power dissipated in antenna (W)
R_r = radiation resistance (ohms)
R_e = effective antenna resistance (ground resistance, ohms)
i = antenna current at the input

Antenna Gain

Directive gain – ratio of the power density radiated in a particular direction to the power density radiated to the same point by a reference antenna (isotropic antenna)
Directivity – maximum directive gain

$$D = \frac{P_D}{P_{D(ref)}}$$

Power gain – same as directive gain, except that antenna efficiency is taken into account

$$A_P = D\eta \; ; \qquad \text{in dB: } A_P = 10\log D\eta$$

For an isotropic antenna, power gain is approximately 1.64 (2.15 dB)

Effective Isotropic Radiated Power (EIRP)

$$EIRP = P_{rad}\, D_t = P_{in}\, A_t$$

Where: P_{rad} = power radiated by an antenna (W)
D_t = transmit antenna directive gain (unitless)
P_{in} = total antenna input power (W)
A_t = transmit antenna power gain (unitless)

To determine the power density at a given distance R from a transmit antenna:

$$P_D = \frac{P_{in}\ A_t}{4\pi R^2} = \frac{P_{rad}\ D_t}{4\pi R^2}$$

Antenna Capture Area

$$A_C = \frac{A_r\ \lambda^2}{4\pi};\quad A_r = \frac{A_C\ 4\pi}{\lambda^2}$$

Captured power:

$$P_{cap} = \frac{P_{in}\ A_t}{4\pi R^2} A_C$$

Where: A_C = effective capture area
λ = wavelength of receive signal
A_r – receive antenna power gain (unitless)
R = distance between transmit and receive antennas

Antenna Polarization – orientation of electric field radiated from the antenna
Antenna Beamwidth – angular separation between two half-power (-3 dB) points on the major lobe of an antenna's radiation pattern

Antenna gain is inversely proportional to beamwidth

Antenna bandwidth – frequency range over which antenna operation is satisfactory
Antenna input impedance or feedpoint – point on the antenna where the transmission line is connected; generally complex

Za = Ra + jXa where: Ra= antenna resistance
Ra = Re + Rr Xa=antenna reactance

Problems:

1. For an antenna with input power of 100 W, rms current of 2 A and effective resistance of 2 ohms, determine the (a) antenna radiation resistance; (b) antenna efficiency; (c) power radiated from the antenna.
   Solution:
   (a) $R_r = \frac{P}{i^2} = \frac{100}{2^2} = 25\Omega$
   (b) $\eta = \frac{R_r}{R_r + R_e} = \frac{25}{25+2} = 92.59\%$
   (c) $\eta = \frac{P_{rad}}{P_{in}}$; $P_{rad} = \eta P_{in} = 0.9259(100) = 92.59W$
2. Determine the power gain in dB for an antenna with a directive gain of 50 dB and efficiency of 75%

$$A_P = 10\log D\eta; \quad 50 = 10\log D; \; D = 100{,}000$$

$$A_P = 10\log[(100{,}000)(0.75)] = 48.75\ dB$$

3. Determine the EIRP in dBm for an antenna with directivity of 33 dB, efficiency of 82% and input power of 100W.

$$EIRP = P_{rad}\ D_t = P_{in}\ A_t$$

$$33 = 10\log D_t; \; D_t = 1995.262$$

$$\eta = \frac{P_{rad}}{P_{in}}; \; P_{rad} = \eta P_{in} = 0.82(100) = 82W$$

$$EIRP = P_{rad}\ D_t = 82(1995.262) = 163{,}611.5098W$$

$$in\ dBm: 10\ \log \frac{163{,}611.5098W}{1x10^{-3}} = 82.13\,dBm$$

4. Find the power density at a point 20 km from an antenna with input power of 1kW and power gain of 23 dB.

$$23 = 10\log A_t; \; A_t = 199.526$$

$$P_D = \frac{P_{in}\ A_t}{4\pi R^2} = \frac{1k(199.526)}{4\pi(20000)^2} = 39.694\mu W/m^2$$

5. A half-wave dipole is driven with a 10-W signal at 200 MHz. A receiving dipole 100 km away is aligned such that the gain is cut in half. Determine the receive power and voltage into the 73-ohm receiver.

   For a half-wave dipole: D = 1.64

   For the wavelength: $\lambda = c/f = 1.5$ m

   Received power:

   $$P_{cap} = \frac{P_{in}\, A_t}{4\pi R^2} A_C = \frac{(10)(1.64)}{4\pi(100k)^2} \frac{(0.5)(1.64)(1.5)^2}{4\pi} = 19.16\, x 10^{-12}\, W$$

   Where:

   $$A_C = \frac{A_r\, \lambda^2}{4\pi} = \frac{(0.5)(1.64)(1.5)^2}{4\pi}$$

   For the voltage received: $P = V^2 / R$; V= **37.4 μV**

   a.

Basic Antenna

Elementary Doublet – an electrically short dipole

Through Maxwell's Equation:

$$E = \frac{60\,\pi\, Il \sin\phi}{\lambda\, R}$$

Where: E = electric field intensity (V/m)

I = dipole current (A, rms)

l = end-to-end length of the dipole

R = distance from the dipole

λ = wavelength

ϕ = angle between the axis of the antenna and the direction of radiation

Since: $P_D = E^2 / 120\pi$:

$$P_D = \frac{30\,\pi\, I^2 l^2 \sin^2\phi}{\lambda^2\, R^2}$$

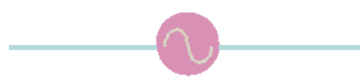
Problem: An elementary doublet is 8-cm long. If the 20 MHz current flowing through it is 3A, what is the field strength 25-km away from the doublet, in a direction of maximum radiation?

For the wavelength: $\lambda = c/f = 15$ m

$$E = \frac{60\pi I l \sin\phi}{\lambda R} = \frac{60\pi(3)(0.08)\sin 90°}{(15)(25k)} = 120.64\mu V/m$$

Half-Wave Dipole

- Generally referred as Hertz antenna
- Widely used at frequencies above 2 MHz
- A resonant antenna (a multiple of quarter wavelength and open-circuited at the far end)



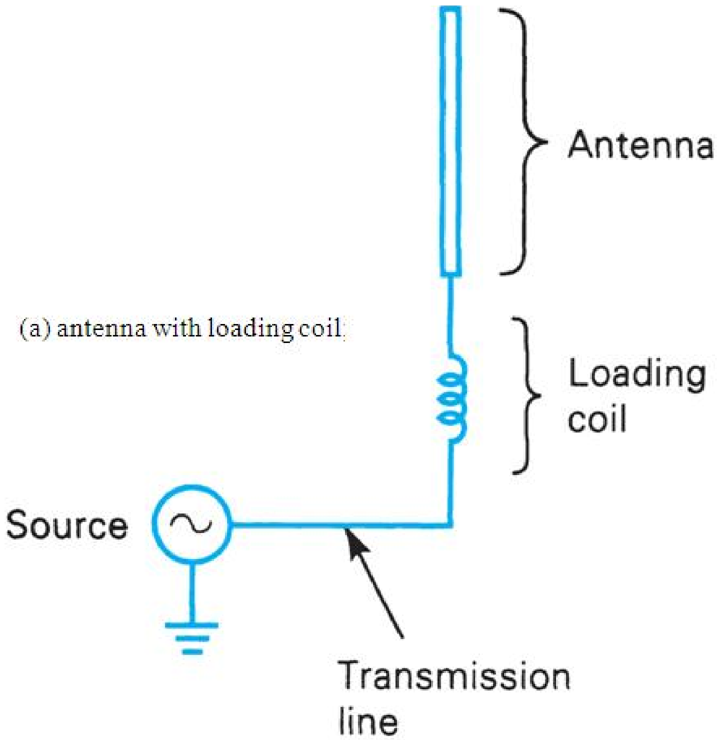
Symbol

Quarter-wave Grounded Antenna

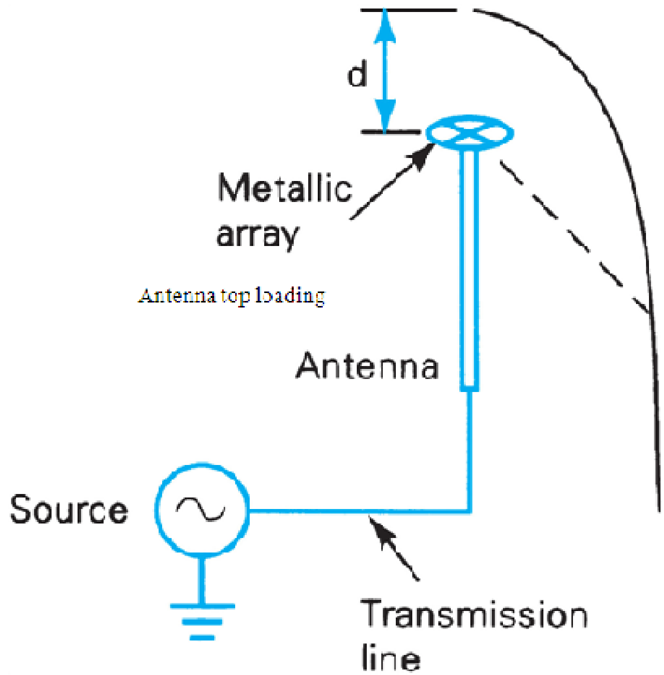
- Monopole (single) antenna one-quarter wavelength long mounted vertically with the lower end either directly connected to ground or through a coupling network
- Also called Marconni antenna
- Charactersitics are similar to the Hertz antenna because of the ground-reflected waves
- Current maxima occurs at the grounded ends
- To reduce power losses, ground should be a good conductor. An alternative way of improving conductivity is through a counterpoise
- Size is only half as long compared to the Hertz antenna but should be located close to ground

Antenna Loading

Physical dimensions for low frequency antennas are not practical. To increase electrical length, loading techniques are applied.



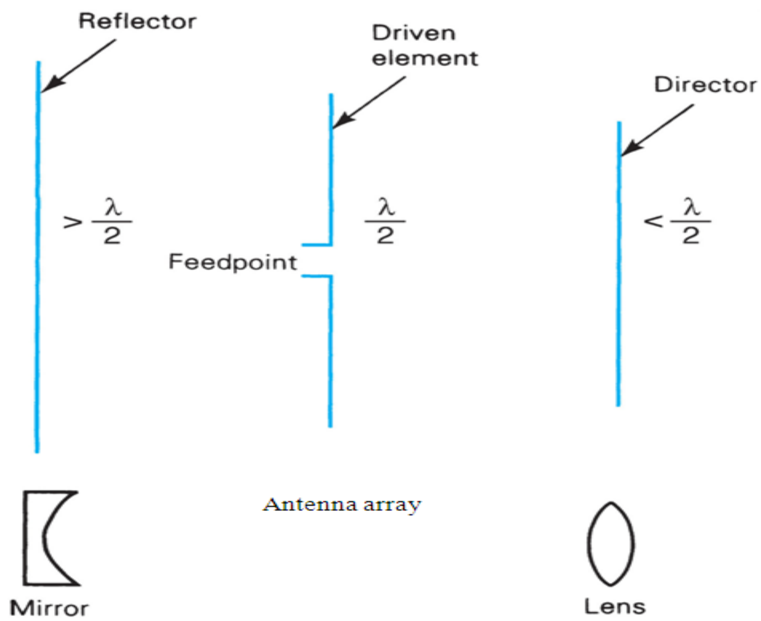
(a) antenna with loading coil



Antenna top loading

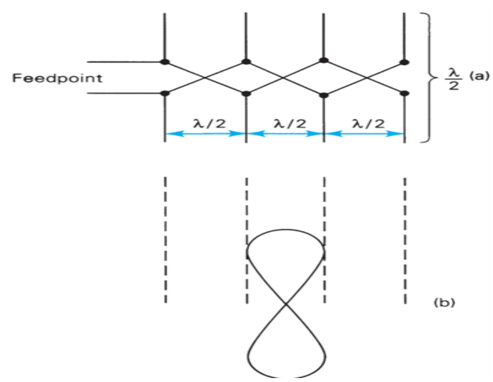
Antenna Arrays

- Formed when two or more antenna elements are combined to form a single antenna
- Increase the directivity of the antenna and concentrates radiated power within a small geographic area
- Antenna elements can be driven or parasitic. Driven elements are directly connected to the transmission line and receive power from the source. Parasitic elements receive energy through mutual induction with a driven or another parasitic element.



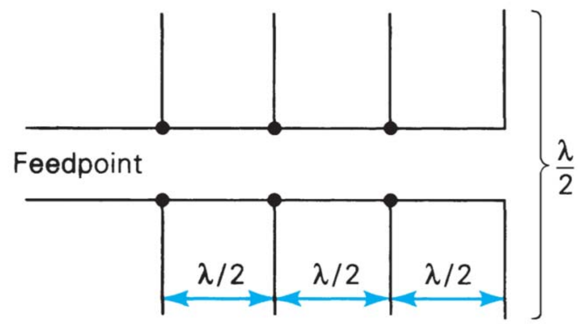
Broadside Array

- Made by placing several resonant dipoles of equal size in parallel with each other and in a straight line. All elements are fed in phase from the source
- Radiates at right angles to the plane of the array and very little to the direction of the plane



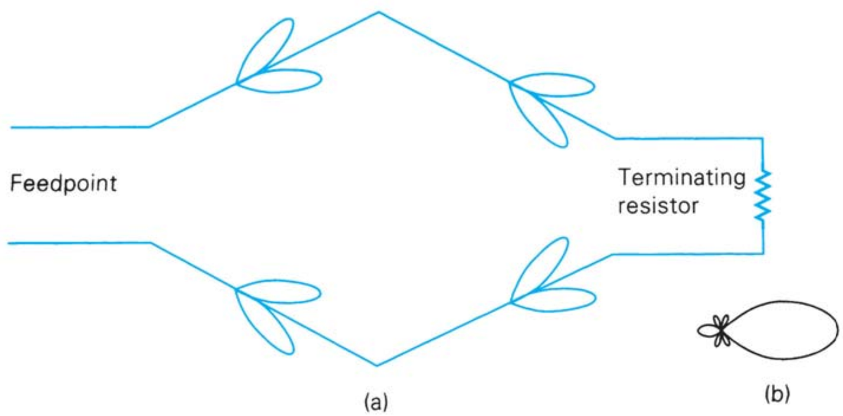
End-fire Array

- Same element configuration as the broadside array except that the transmission line is not crisscrossed between elements



Rhombic Antenna

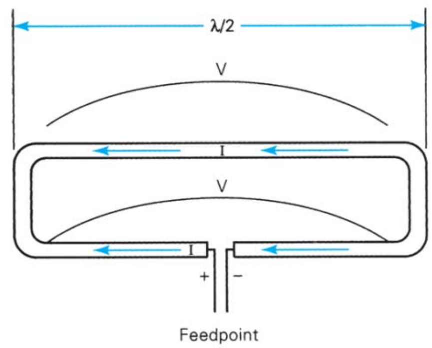
- A nonresonant antenna suited for HF transmission
- Made up of four nonresonant elements terminated in a resistor



Special-Purpose Antennas

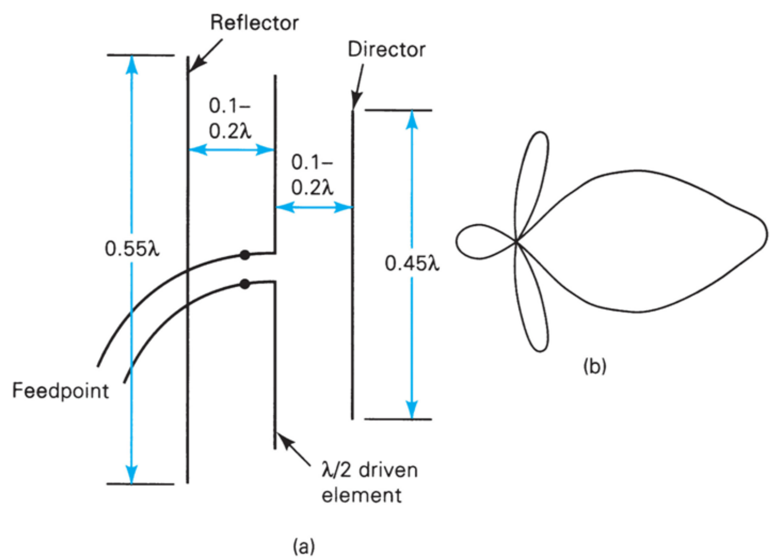
Folded Dipole

- A single antenna made up of two elements
- Input impedance is equal to half-wave impedance (72 Ω) times the square of the number of folded wires. ($2^2 * 72 = 288\ \Omega$)



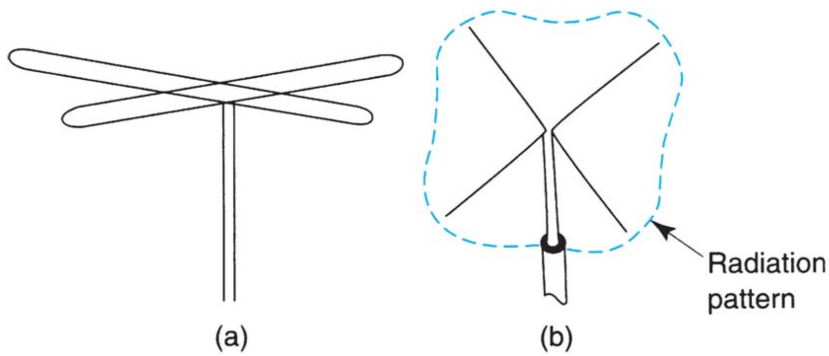
Yagi-Uda Antenna

- A linear array consisting of a dipole and two or more parasitic elements: one reflector and one or more directors
- Commonly used for VHF TV transmission



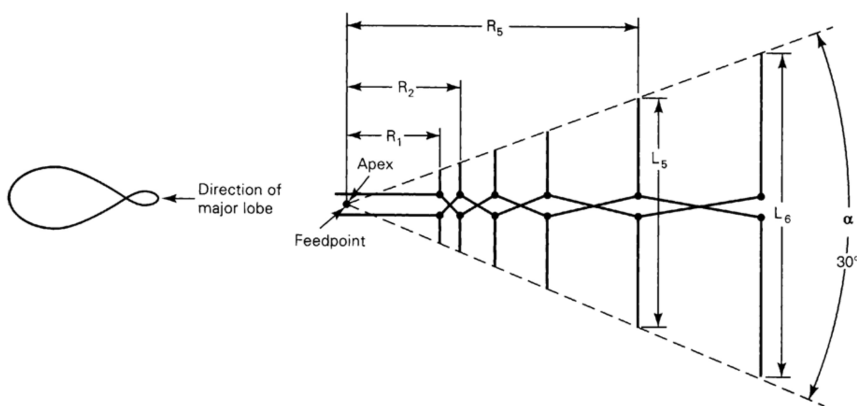
Turnstile Antenna

- Formed by placing two dipoles at right angles to each other (90 degrees out of phase)
- Radiation pattern produces nearly an omnidirectional pattern



Log-Periodic Antenna

- Consists of several dipoles of different length and spacing that are fed from a single source at the small end. The transmission line is crisscrossed between the feedpoints of adjacent pairs of dipoles
- Advantage: independent of radiation resistance and radiation pattern to frequency
- Not a type of antenna but a class of antenna
- Physical structure is repetitive, making electrical characteristics repetitive as well



Formula for dipole length and spacing:

$$\frac{R_2}{R_1} = \frac{R_3}{R_2} = \frac{R_4}{R_3} = \frac{1}{\tau} = \frac{L_2}{L_1} = \frac{L_3}{L_2} = \frac{L_4}{L_3}$$

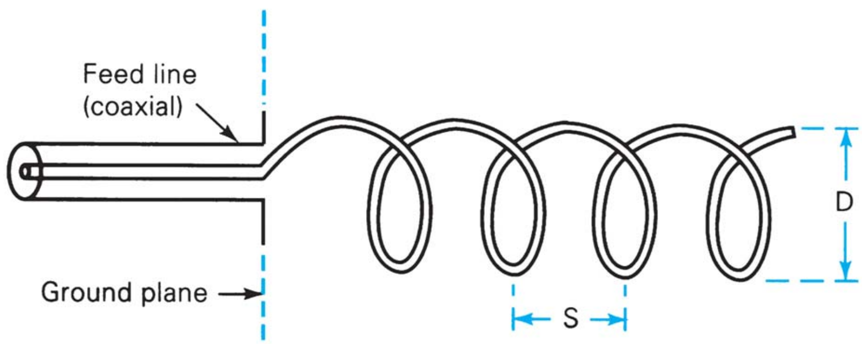
$$\frac{1}{\tau} = \frac{R_n}{R_{n-1}} = \frac{L_n}{L_{n-1}}$$

Where: R = dipole spacing
L = dipole length
τ = design ratio (less than 1)

For a typical design: $\tau = 0.7$; $\alpha = 30°$

Helical Antenna

- A broadband VHF or UHF antenna suited for applications for which radiating circularly-polarized electromagnetic waves are required
- Mounted on a ground plane made up of either solid metal or metal screen
- Two modes of propagation are available: normal and axial.



Power Gain of a Helical Antenna

$$A_p(dB) = 10\log[15(\frac{\pi D}{\lambda})^2 \frac{(NS)}{\lambda}]$$

Where: A_p (dB) = antenna power gain (dB)

D = helix diameter (m)

N = number of turns

S = pitch

λ = wavelength

3-dB Beamwidth of a Helical Antenna

$$\theta = \frac{52}{(\pi D/\lambda)(\sqrt{NS/\lambda})}$$

Problem: Determine the power gain and beamwidth for an end-fire helical antenna with the following parameters: helix diameter = 0.1 m, number of turns = 10, pitch = 0.05 m and frequency of operation = 500 MHz

Solution

$$\lambda = \frac{c}{f} = \frac{3x10^8}{500x10^6} = 0.6m$$

$$A_p(dB) = 10\log[15(\frac{\pi D}{\lambda})^2 \frac{(NS)}{\lambda}] = 10\log[15(\frac{0.1\pi}{0.6})^2 \frac{(10 * 0.05)}{0.6}] = 5.349\,dB$$

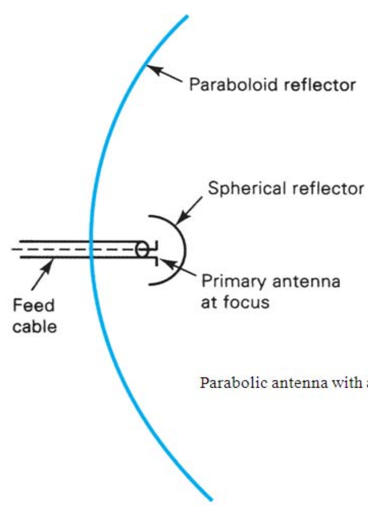
$$\theta = \frac{52}{(\pi D/\lambda)(\sqrt{NS/\lambda})} = \frac{52}{(\pi * 0.1/0.6)(\sqrt{10 * 0.05/0.6})} = 108.79°$$

UHF and Microwave Antennas

- Should be highly directive
- Concentrates power in a narrow beam (beamwidth decreases with increasing antenna gain)
- Highly directional antennas are used with point-to-point microwave systems

Parabolic Antenna

- Consists of a parabolic reflector and the feed mechanism
- Feed mechanism radiates the energy toward the reflector (center feed, horn feed, Cassegrain feed)
- Parabolic reflectors are sometimes called parabolic dish antennas
- All waves radiated toward the parabola from the focus will be in phase when they reach the directrix, regardless from which point on the parabola they are reflected



Parabolic antenna with a center feed

Parabolic Antenna Beamwidth

$$\theta = \frac{70\lambda}{D}$$

Beamwidth between nulls: $\phi_0 = 2\theta$

Parabolic Antenna Power Gain (with respect to an isotropic antenna)

$$A_p = \eta(\frac{\pi D}{\lambda})^2$$

Problem: Determine the beamwidth and transmit and receive power gains of a parabolic antenna with the following parameters: dish diameter of 2.5 m, frequency of operation of 4 GHz, and a 55% efficiency.

$$\lambda = \frac{c}{f} = \frac{3x10^8}{4x10^9} = 0.075m$$

$$\theta = \frac{70\lambda}{D} = 70\frac{0.075}{2.5} =$$

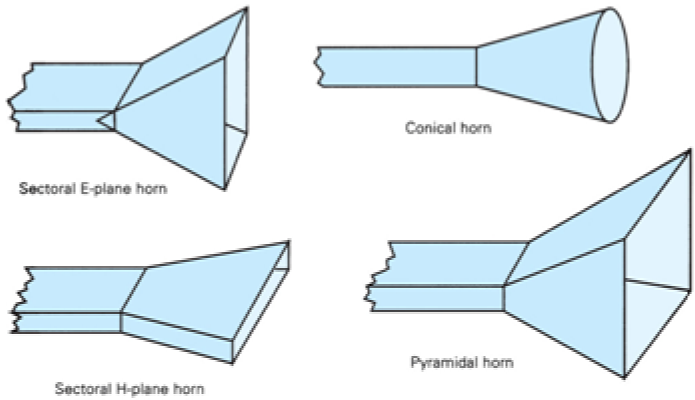
$$A_p = \eta(\frac{\pi D}{\lambda})^2 = 0.55(\frac{2.5\pi}{0.075})^2$$

Horn Antenna

To overcome the difficulties in radiating energy using a waveguide, the mouth of the waveguide maybe opened out, as was done to the transmission line, but this time an electromagnetic horn results instead of the dipole.

There are several possible horn configurations, the most common are

(a) *Sectoral horn* – flares out in one direction only.
(b) *Pyramidal Horn* – flares out in both direction and has the shape of a truncated pyramid
(c) *Conical Horn* – flares out in both directions and is a logical termination for a circular waveguide.



Special horn antennas are the Cass-horn and the Hoghorn antenna, which are rather difficult to classify since each is a cross between a horn and a parabolic reflector.

Lens Antenna

The lens antenna is yet another example of how optical principles may be applied to microwave antennas. It is used as a collimator at frequencies well in excess of 3 GHz and works in the same way as a glass lens used in optics.