Antenna :
Fundamentals and Practice

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Antenna Concept

- Mode conversion point of view:

  A transition device between a guided wave and a space wave.

- Energy conversion point of view:

  A converter between photons and currents.

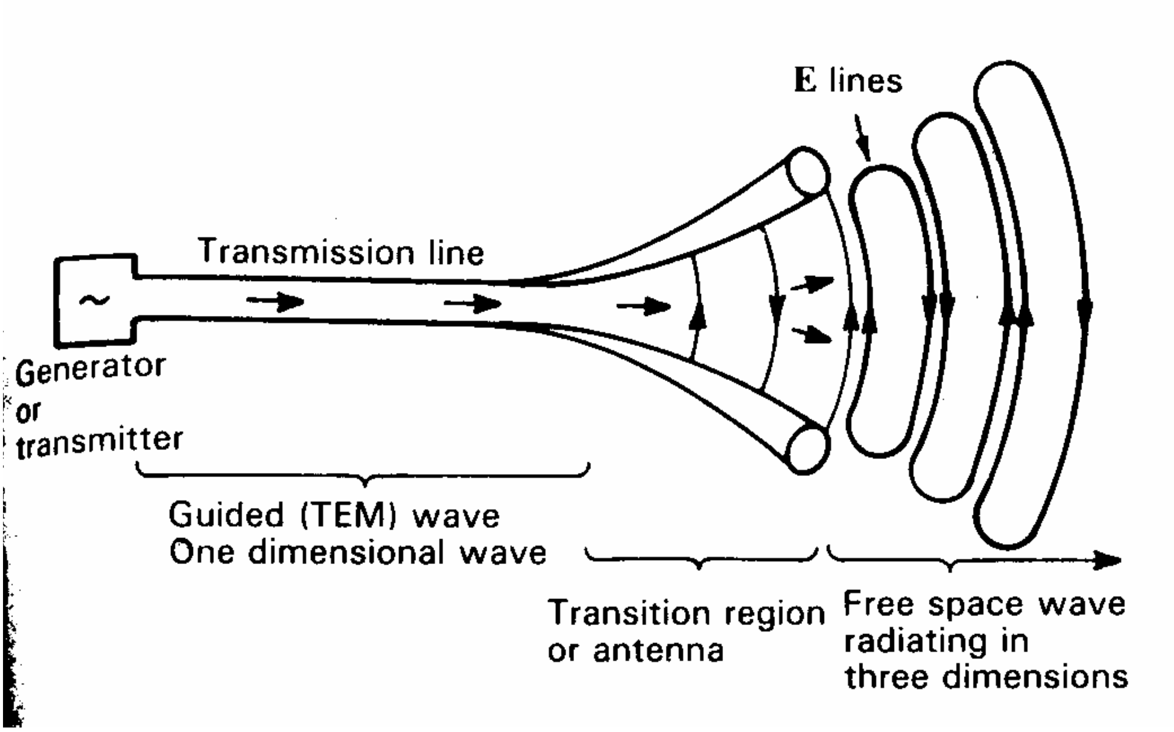
- Circuit point of view:

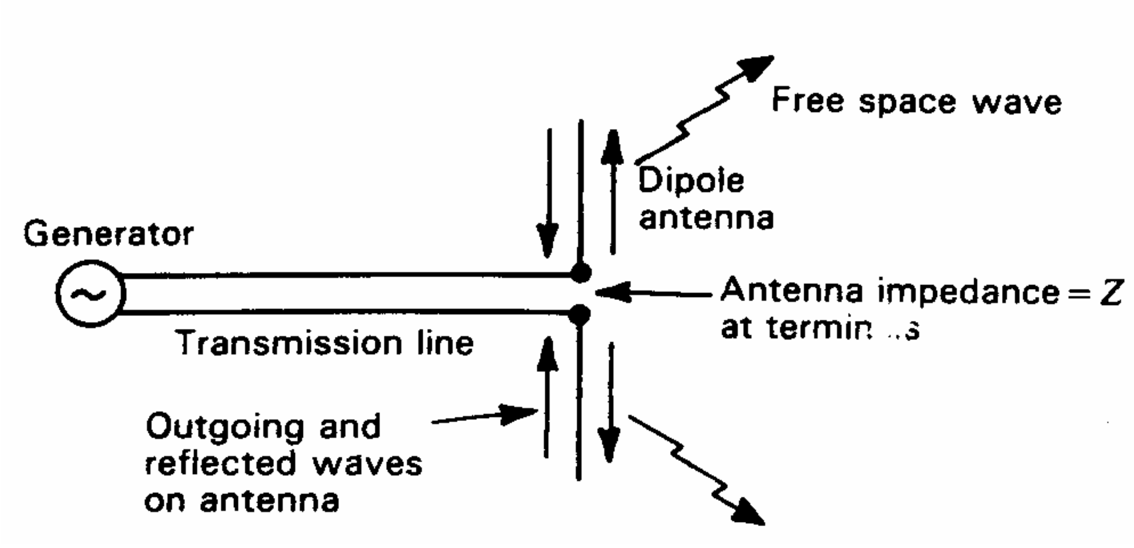
  One-port black box with input impedance Z_{in}.

- Signal transmission point of view:

  A spatial filter.

Conceptual antenna





Sources of Radiation

- Maxwell’s equations in time-domain

$$\nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{\partial \mathbf{B}(\mathbf{r},t)}{\partial t} : \text{Faraday's law}$$

$$\nabla \times \mathbf{H}(\mathbf{r},t) = \mathbf{J}(\mathbf{r},t) + \frac{\partial \mathbf{D}(\mathbf{r},t)}{\partial t} : \text{Ampere's law}$$

$$\nabla \cdot \mathbf{D}(\mathbf{r},t) = \rho(\mathbf{r},t) : \text{Gauss' law}$$

$$\nabla \cdot \mathbf{B}(\mathbf{r},t) = 0 : \text{Gauss' law}$$

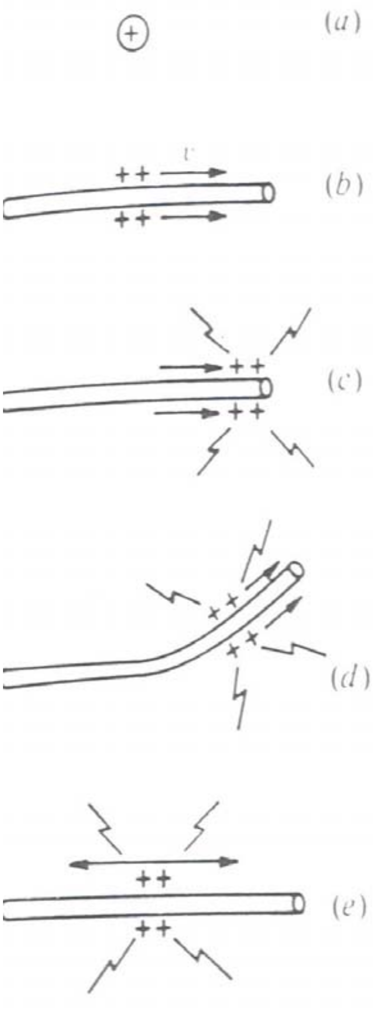
$$\nabla \cdot \mathbf{J}(\mathbf{r},t) = -\frac{\partial \rho(\mathbf{r},t)}{\partial t} : \text{continuity equation}$$

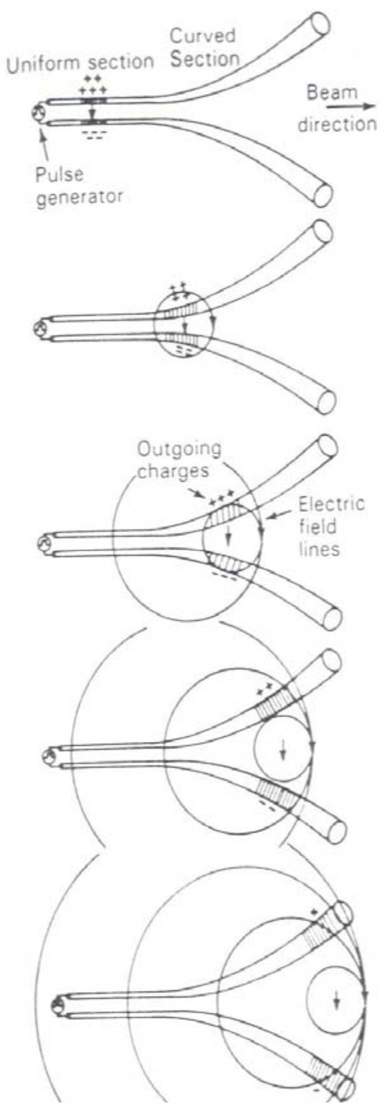
- accelerated ⇔ time varying
  charges currents

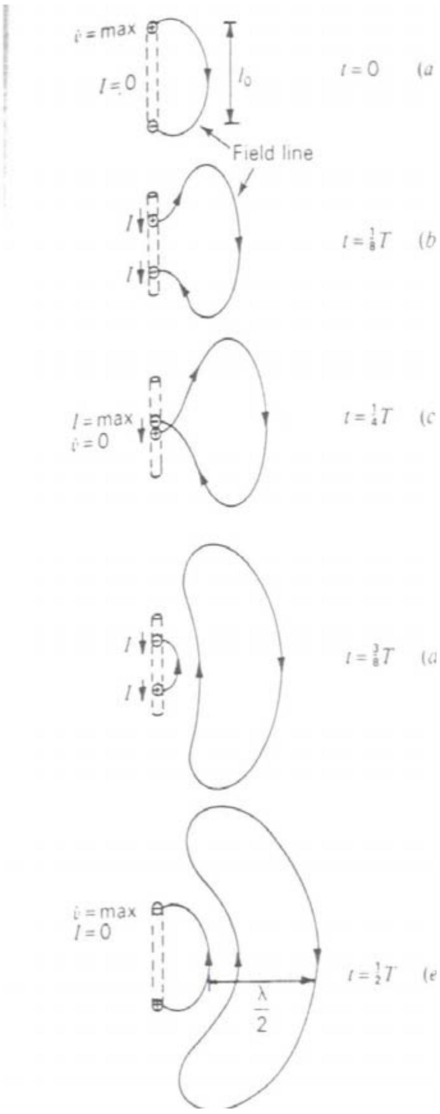
←

Electromagnetic Field Radiation

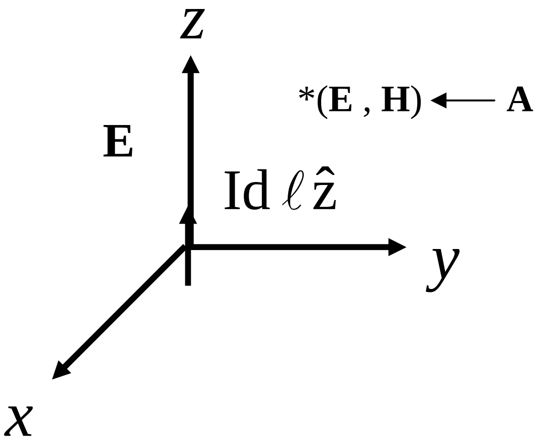
Charge accelerating structures







Radiation from a short current filament



$*(\mathbf{E}\ ,\ \mathbf{H}) \longleftarrow \mathbf{A}$

$$\mathbf{A}(r) = \frac{e^{-jk_0 r}}{4\pi r}\,\mu_0 I d\ell\ \hat{z}$$

$$\mathbf{H} = \frac{I d\ell \sin\theta}{4\pi}\left(\frac{jk_0}{r} + \frac{1}{r^2}\right)e^{-jk_0 r}\hat{\phi}$$

$$\mathbf{E} = \frac{jZ_0 I d\ell}{2\pi k_0}\cos\theta\left(\frac{jk_0}{r^2} + \frac{1}{r^3}\right)e^{-jk_0 r}\hat{r}$$

$$-\frac{jZ_0 I d\ell}{4\pi k_0}\sin\theta\left(-\frac{k_0^{\ 2}}{r} + \frac{jk_0}{r^2} + \frac{1}{r^3}\right)e^{-jk_0 r}\hat{\theta}$$

Characteristics of short dipole(I)

- In far-field region $(r \gg \lambda_0 , r \gg dl , r > \frac{2 dl^2}{\lambda})$

$$\mathbf{E} = jZ_0 Id\ell k_0 \sin\theta \frac{e^{-jk_0 r}}{4\pi r}\hat{\theta}$$

$$\mathbf{H} = jId\ell k_0 \sin\theta \frac{e^{-jk_0 r}}{4\pi r}\hat{\phi}$$

1. proportional to I, dl(linear superposition)
2. propagate in the r-direction with E_θ, H_ϕ only(TEM wave)
3. $\frac{E_\theta}{H_\phi} = 377\,\Omega$ (E_θ, H_ϕ in time phase)
4. sin θ space-variation(signaling)
5. $\frac{1}{r}$ distance dependence(power conservation)
6. $e^{-jk_0 r}$ phase dependence(propagation delay)

Characteristics of short dipole(II)

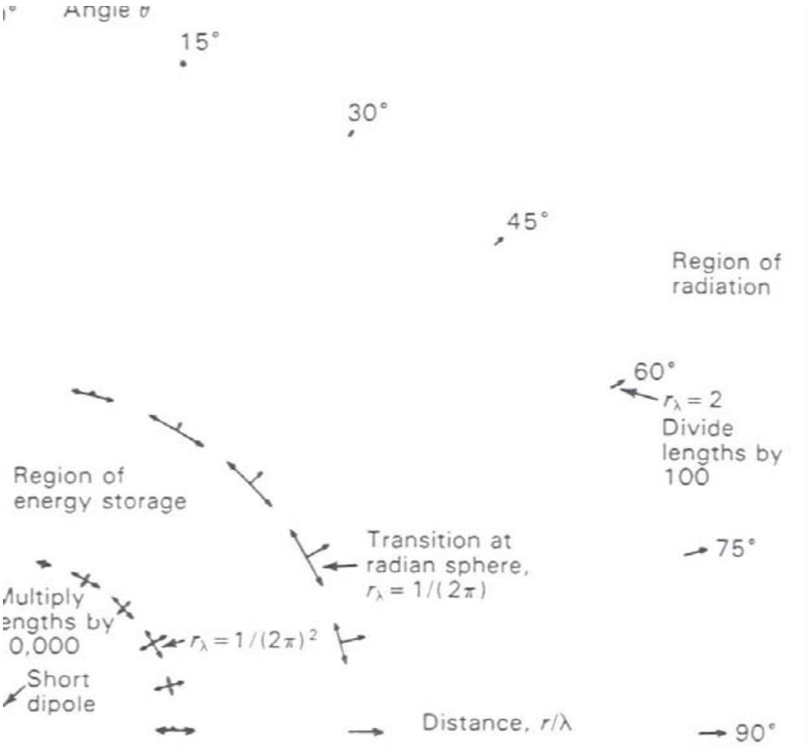
- In near-field region(quasi-stationary)

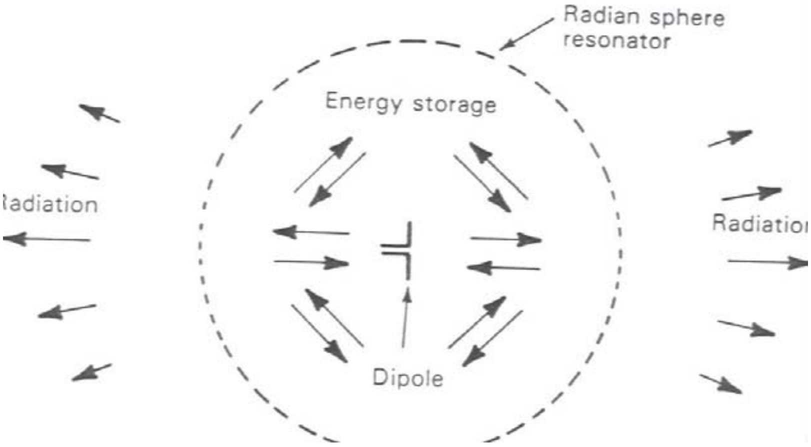
$$\mathbf{H} = \frac{Id\ell \sin\theta}{4\pi r^2}\hat{\phi} \rightarrow \text{static magnetic field}$$

$$\mathbf{E} = \frac{Qd\ell}{4\pi}\left(\frac{2\cos\theta}{r^3}\hat{r} + \frac{\sin\theta}{r^3}\hat{\theta}\right) \rightarrow \text{dipole fields}$$

1. Electric fields(E_r, E_θ) in time phase quadrature with H_ϕ: energy storage in resonator
2. sin θ variation of E_θ, H_ϕ and cos θ variation of E_r components
3. $\frac{1}{r^2}$ or $\frac{1}{r^3}$ dependence: confinement of field in vicinity of dipole(radian distance $r \le \frac{\lambda}{2\pi}$)

Power flux with distance





Radiation patterns

- Representation of radiation as a function of direction in space
- 2-D/ 3-D pattern

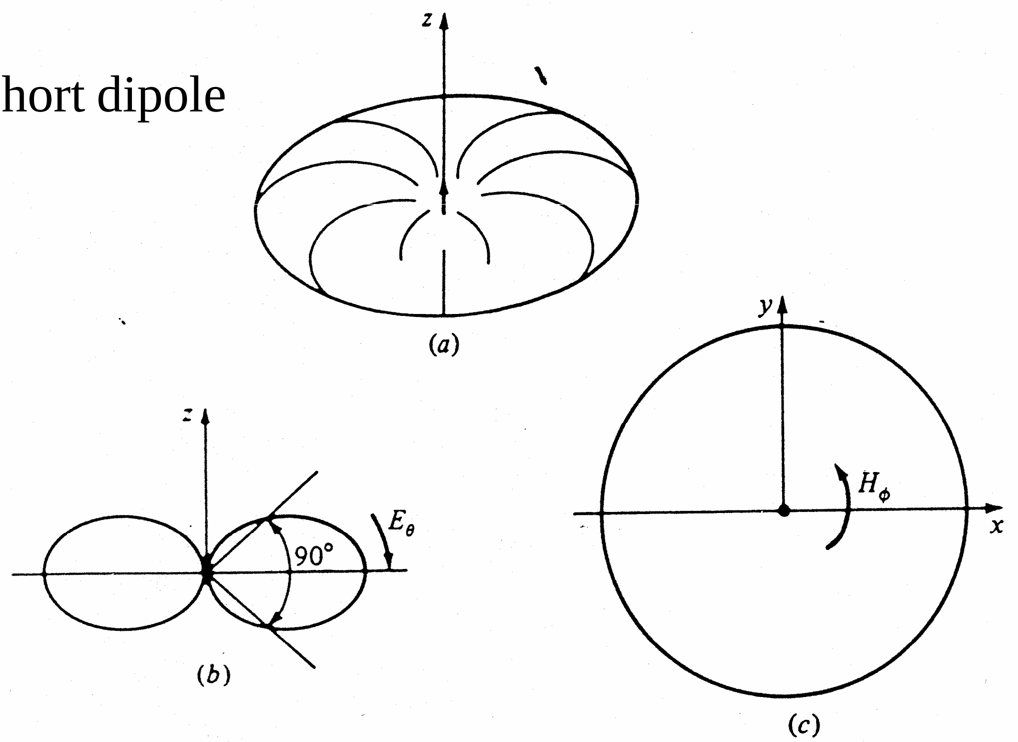
1. E-plane pattern :

   plane including maximum radiation direction and electric field direction

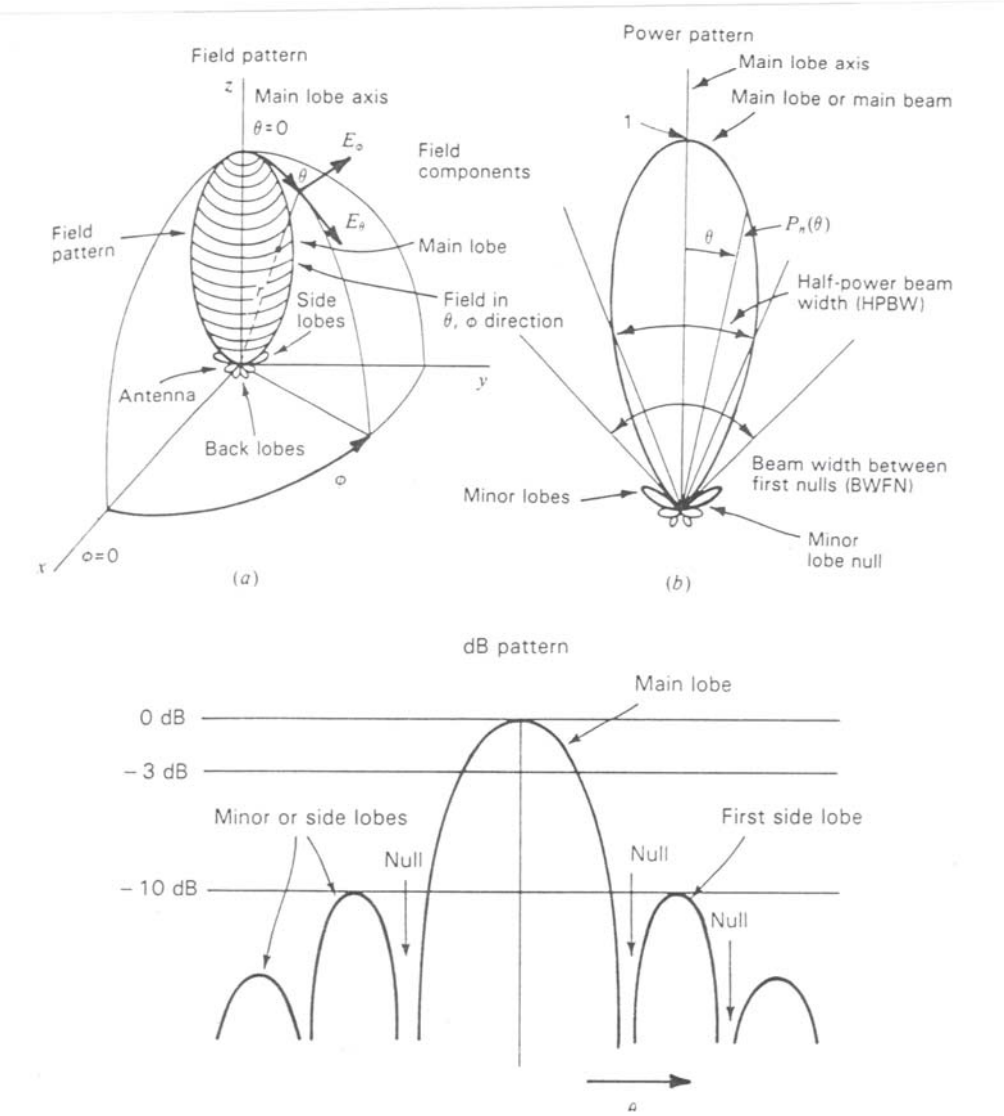
2. H-plane pattern :

   plane including maximum radiation direction and magnetic field direction

short dipole



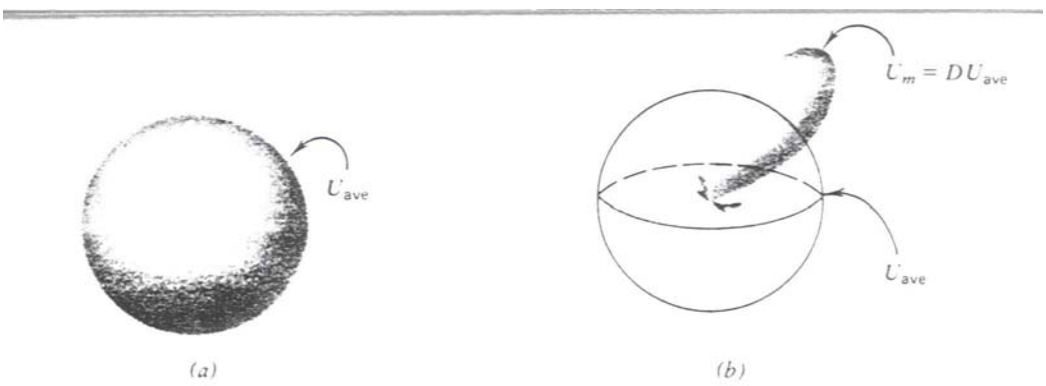
Pattern Examples



Directivity, Gain

- Directivity : D (dimensionless)

1. Ratio of the maximum radiation intensity to the average radiation intensity
2. $D = \frac{U(\theta,\phi)_{\max}}{U_{av}} = \frac{U(\theta,\phi)_{\max}}{P_r / 4\pi}$



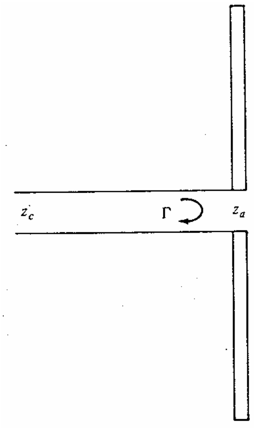
- Gain : G

1. Depends on both directivity and efficiency
2. G=ηD

   where η =efficiency factor of antenna(0< η <1)
3. Due to Ohmic losses in the antenna

Antenna Input Impedance

- Input impedance



$$\Gamma = \frac{Z_a - Z_c}{Z_a + Z_c}$$

$$Z_a = Z_c \frac{1+\Gamma}{1-\Gamma}$$

$$Z_a = \frac{V_a}{I_a}$$

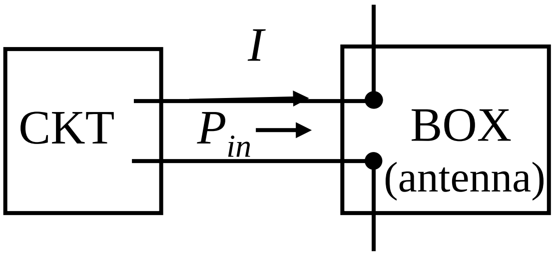
$$= \frac{P_r + P_d + 2j\omega\left(W_m - W_e\right)}{\frac{1}{2}\left|I_0\right|^2}$$

Where P_r : radiated power
P_d : ohmic loss of antenna
W_m : storage of magnetic energy
W_e : storage of electric energy

$\}$ Near field contribution only

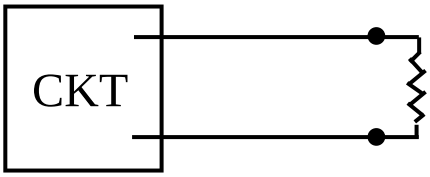
Radiation resistance
Loss resistance

- Antenna input resistance :
  radiation loss and Ohmic loses



$$\begin{aligned} P_{in} &= P_r + P_{loss} \\ &= \frac{1}{2}\left|I\right|^2 R_a \end{aligned}$$

⇓



$R_a = R_r + R_{loss}$

- Input reactance :
  near-field energy storage

$$jX = \frac{2j\omega\left(W_m - W_e\right)}{\frac{1}{2}\left|I_0\right|^2}$$

Antenna efficiency

- Antenna efficiency : η

$$\eta = \frac{P_r}{P_{in}} = \frac{R_r}{R_r + R_{loss}}$$

Ex) for small dipole

$$R_r = \frac{2P_r}{|I|^2} = 80\pi^2\left(\frac{d\ell}{\lambda_0}\right)^2$$

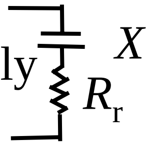
$$d\ell = 1m \quad , \quad f = 1MH_Z \quad (\lambda = 300m)$$

$$R_r = 0.0084\Omega$$

matching element loss

$$\Rightarrow \begin{cases}\text{high reactance}\\ \text{small resistance}\end{cases}$$

equivalently



$X >> R_r$: low efficiency

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very low gain

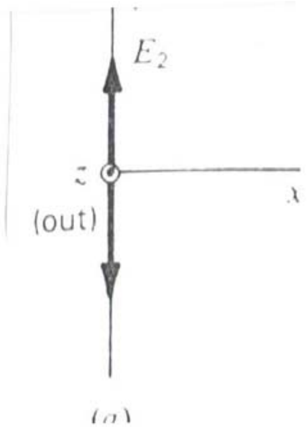
An Efficient antenna must be comparable to a wave length in size!

Polarization

- The orientation of the electric field E.

(1) linear polarization

- horizontal
- vertical

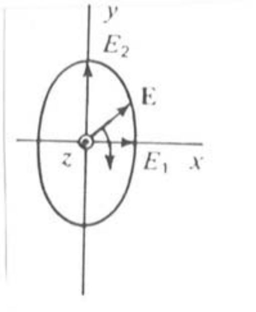


(a)

(2) elliptical polarization

- axial ratio:

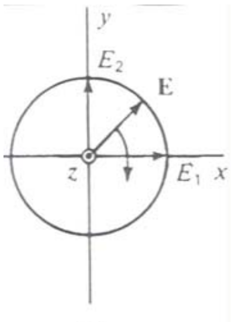
$$AR = \frac{E_2}{E_1} \quad (1 \le AR \le \infty)$$



(b)

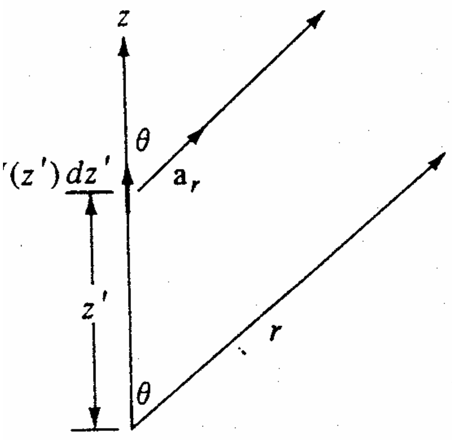
(3) circular polarization

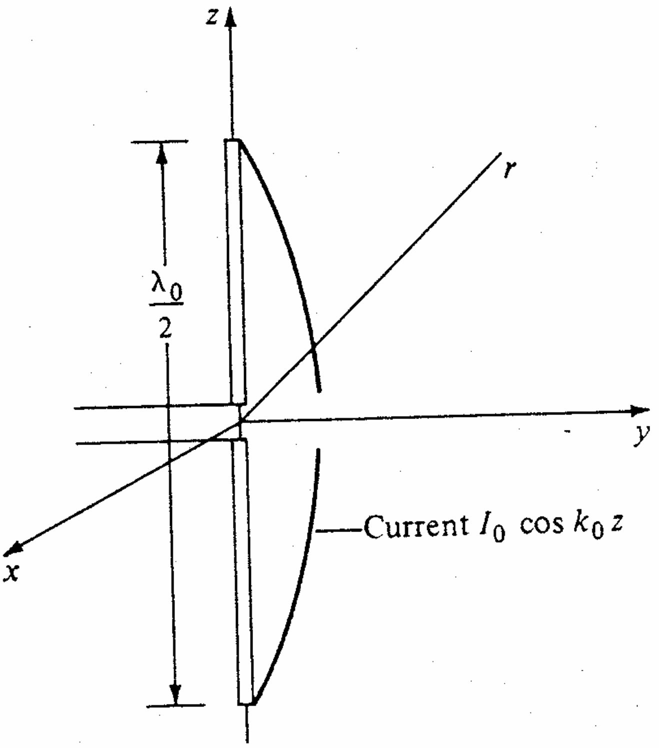
- right-hand
- left-hand



(c)

Half-wave dipole antenna



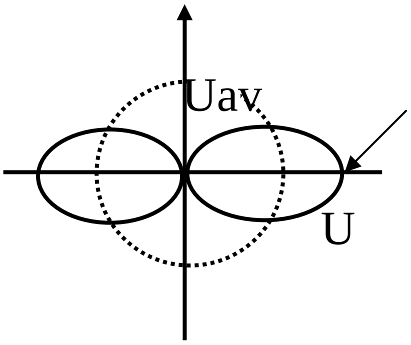


$$\mathbf{E}(\mathbf{r}) = \frac{jI_0 Z_0}{2\pi r} e^{-jk_0 r} \frac{\cos\left(\frac{\pi}{2}\cos\right)}{\sin\theta}\hat{\theta}$$

$$\mathbf{H}(\mathbf{r}) = \frac{1}{Z_0}\hat{r}\times\mathbf{E}(\mathbf{r}) = \frac{jI_0}{2\pi r} e^{-jk_0 r} \frac{\cos\left(\frac{\pi}{2}\right)}{\sin\theta}\hat{\phi}$$

Characteristics of half-wave dipole

1. Directivity : $$D(\theta,\phi) = 1.64\left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}\right]^2$$



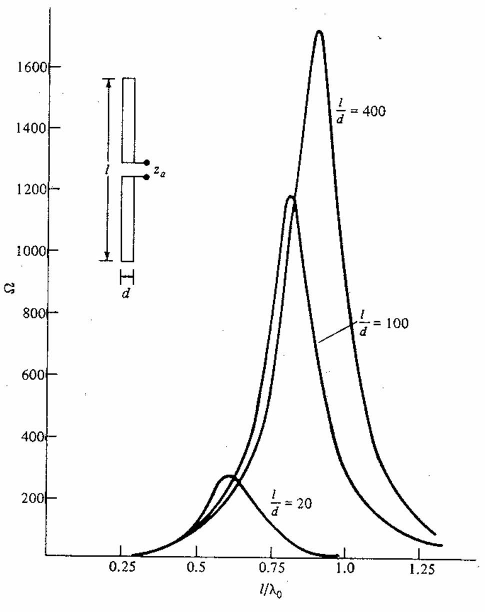
D=1.64 (2.15 *dB*)

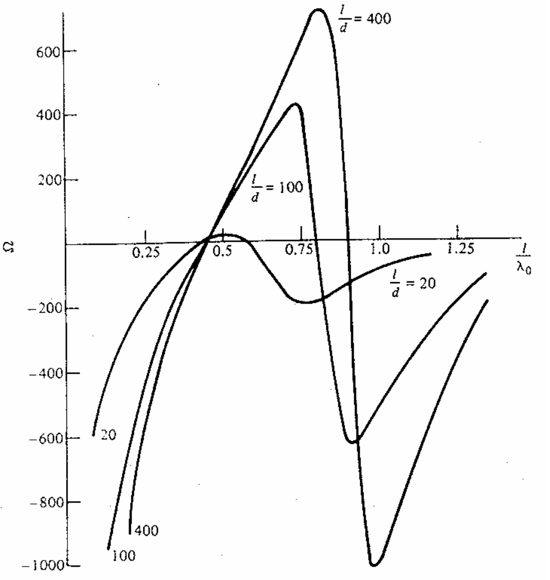
HPBW : 78°

2. Radiation Resistance :

$Ra \cong 73\Omega$ >> Ohmic losses

3. Input impedance :





(1) resonance near $\frac{\lambda_0}{2}$: half wave dipole

(0.48 λ_0)

resonance near λ_0 : parallel resonance (R_a is large)

(2) thicker antenna → wide band characteristic

(3) $\ell / \lambda_0 << \frac{1}{2}$

- Ra is very small
- large capacitive reactance
- inductor tuning → additional Ohmic loss → lower efficiency
- small bandwidth

(4) The junction capacitance and surrounding structures influence in Z_a

Principal use of small antennas

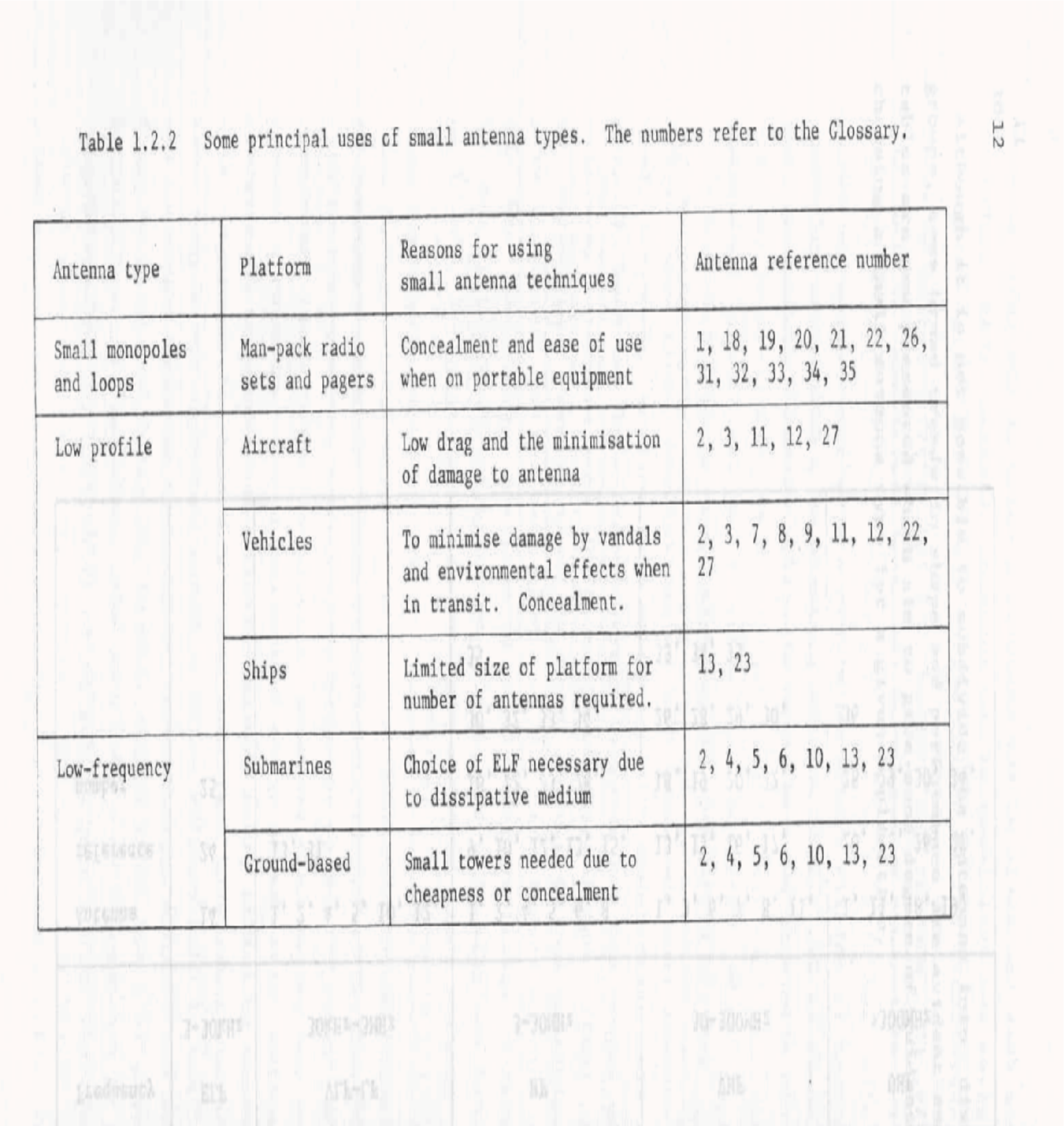
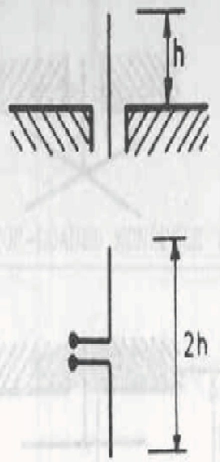


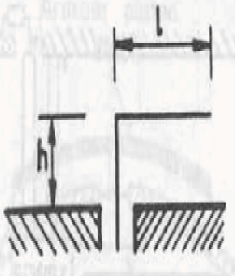
Table 1.2.2 Some principal uses of small antenna types. The numbers refer to the Glossary.

Antenna type	Platform	Reasons for using small antenna techniques	Antenna reference number
Small monopoles and loops	Man-pack radio sets and pagers	Concealment and ease of use when on portable equipment	1, 18, 19, 20, 21, 22, 26, 31, 32, 33, 34, 35
Low profile	Aircraft	Low drag and the minimisation of damage to antenna	2, 3, 11, 12, 27
	Vehicles	To minimise damage by vandals and environmental effects when in transit. Concealment.	2, 3, 7, 8, 9, 11, 12, 22, 27
	Ships	Limited size of platform for number of antennas required.	13, 23
Low-frequency	Submarines	Choice of ELF necessary due to dissipative medium	2, 4, 5, 6, 10, 13, 23
	Ground-based	Small towers needed due to cheapness or concealment	2, 4, 5, 6, 10, 13, 23



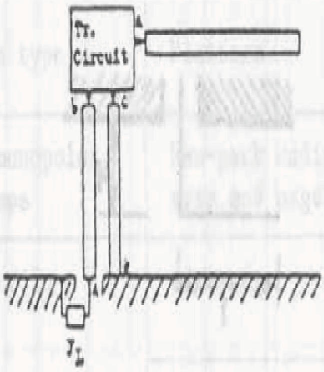
1. SHORT MONOPOLE

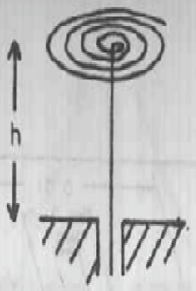
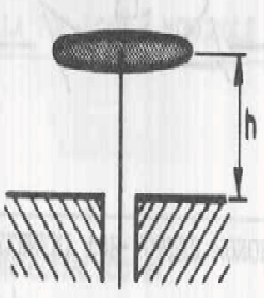
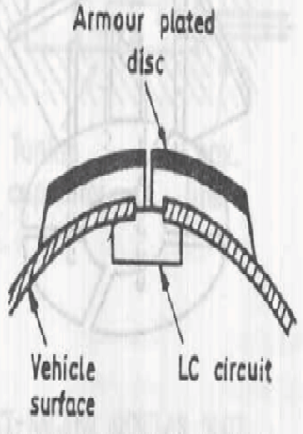
The simple thin monopole has a low radiation resistance $r_r \sim 40\pi^2(h/\lambda)^2$ and is highly capacitive (Jasik, 1952, p3-2). When tuned and matched at the input, a low efficiency generally results due to power losses in the matching circuits. Typically for $h/\lambda \sim 0.05$, efficiencies of 30-70% for bandwidths of 10-1% are attainable after matching (Seeger, 1959; Schroeder and Soo Hoo, 1976). The short dipole has twice the value of r_r and requires a balanced feeder arrangement. See also inductively-loaded monopole (Glossary No 18).

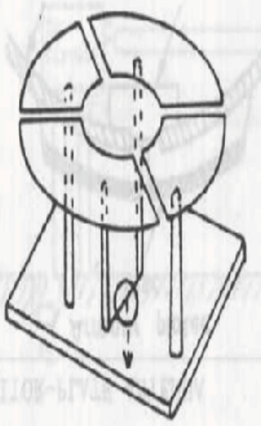
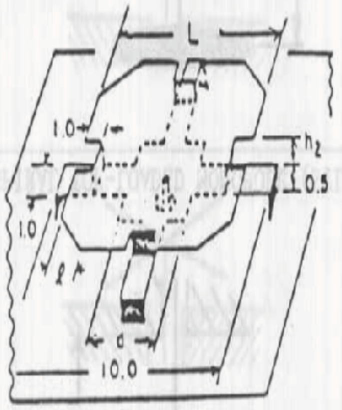


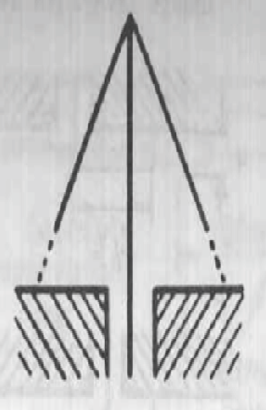
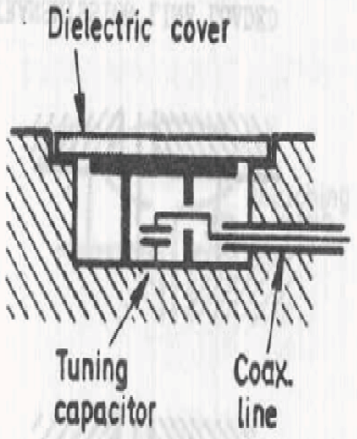
2. INVERTED L-

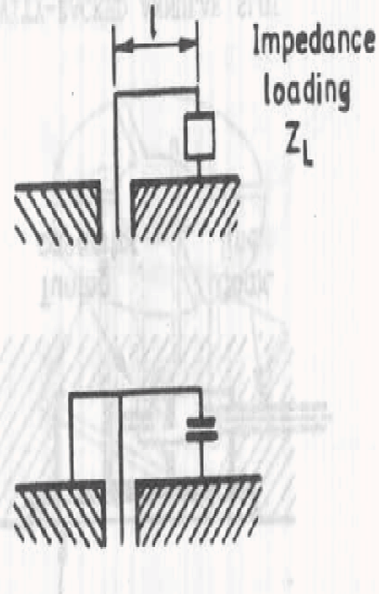
On top loading a short monopole, the current distribution tends to become more uniform along its length and this increases the radiation resistance. The inverted L antenna is the simplest form of top loaded antenna and is used at HF and below (Pierce, 1920; Harrison, 1958; King and Harrison, 1949; Prasad and King, 1961). Simpson (1969, 1971) quotes an input impedance of about 5 ohms for $h/\lambda \sim 0.05$: the input impedance can be brought to resonance by adjusting ℓ so that $h+\ell \sim \lambda/4$. The inverted L- antenna is mentioned again under transmission-line loaded antennas (Glossary No 12)(Guertler, 1977).

 3. ACTIVE IL	The transistor-loaded inverted L- antenna has been treated by Hiroi and Fujimoto (1970) and Fujimoto (1970) and shown to be useful in shifting the direction of the maximum in the antenna pattern by varying the bias supply to the Tr-circuit. The application of these devices in VHF receivers is considered in Section 2.4.2. Further examples of active antennas are given later and the concept of integrated antenna systems is described by Fujimoto (1970).
 4. TWO-OR-FOUR-ELEMENT TOP-LOADED MONOPOLE	Simpson (1971) has calculated the input impedance of several multi-element top-loaded monopoles. These antennas have approximately the same radiation resistance as the inverted L but are usually operated below self-resonance and consequently need tuning and matching circuits.

 5. SPIRAL TOP-LOADED MONOPOLE (STLA)	The STLA is used at HF and VLF having the advantage over most other top-loaded antennas, in that it is self-resonant and requires no tuning inductors. Bhojwani and Zelby (1973) give the radiation resistance and losses. Typically an antenna with $h \sim 0.02\lambda$ over lossy earth will have an efficiency of 10% with an impedance of 6 ohms, mainly contributed by the soil.
 6. CAPACITOR-PLATE ANTENNA	The capacitor plate antenna is a form of top-loaded antenna which has a radiation resistance of $160\pi^2(h/\lambda)^2$ (Weeks, 1968) - this is four times that of a monopole of the same length. Versions of this antenna are used for low-profile applications, as given below.
 7. LOW-PROFILE VEHICULAR ANTENNA	This VHF antenna is loaded with dielectric material to obtain a very low profile $(\sim\lambda/60)$ and robust design for use on vehicles (Goubau, 1976). It covers the band from 30-80MHz by using an automatic tuning circuit and has an efficiency of between 11 and 70%.

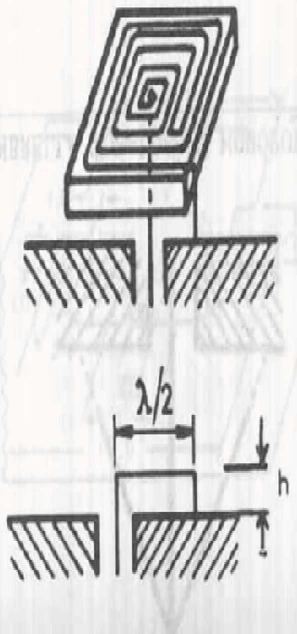
 8. MULTI-ELEMENT TOP-LOADED MONOPOLE	This antenna is also based on the disc-loaded monopole but some increase in bandwidth has been achieved by mutual coupling between elements (Goubau, 1976). The top disc has been segmented into four sections and each is excited by a small monopole. The radiation resistance is increased to 50 ohms by this means.
 9. MULTI-PLATE	A similar low-profile antenna to the above has been developed by Tokumaru (1976) and consists of two metal plates. The lower plate is connected to the ground and the upper plate is connected to the lower. The size of the lower plate determines the lowest operating frequency whereas the upper plate determines the VSWR characteristics. Typically a VSWR of 1.4 can be obtained between 1.2 and 2GHz.

 10. UMBRELLA TOP-LOADED MONOPOLE	Mainly used as a VLF or LF antenna when low cost and low wind resistance are important. The guy wires act as a top loading and can increase the radiation resistance to 10 ohms for $h \approx 0.1\lambda$ (Gangi et al, 1965). The antenna is usually operated below resonance but can readily be made resonant by adjusting the length of the guy wires. The radiation efficiency is similar to that of the T and L type antennas but requires only one tower for installation (Goubau, 1976).
 11. CAVITY-BACKED ANNULAR SLOT	The cavity-backed slot is particularly used on aircraft and on vehicles at VHF and UHF where a flush surface is required. The radiating annular slot is matched to the coaxial feed by means of a tuning capacitor and a coupling loop. It has a radiation resistance of about 100 ohms for a 0.5λ diameter (Cumming and Cormier, 1958).



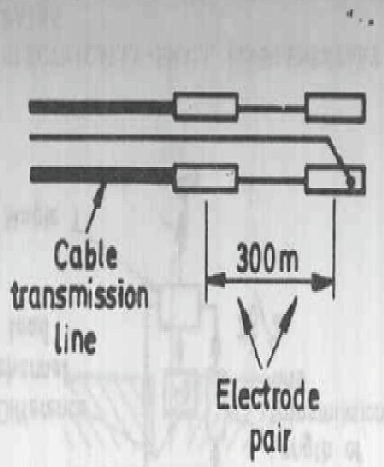
12. TRANSMISSION LINE LOADED

The inverted L- is a special case of the transmission-line antenna (or 'tranline') where $Z_L = \infty$. Tranlines exist in a wide variety of forms and have been used as missile or vehicle antennas where the body constitutes the ground-plane (King et al.,1960). More recently (Goubau, 1976, p129), tranlines fitted with automatic tuning for use on helicopters have achieved efficiencies of between 90 and 8% in the 2-5MHz band, for $\ell \sim \lambda/50$. In this particular case the dipole mode is excited in the helicopter frame thus increasing the efficiency at low frequency.



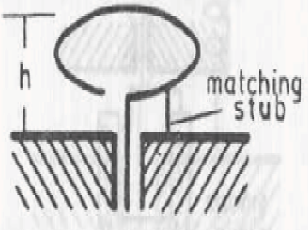
13. PLANAR HALF-WAVE WOUND TRANSMISSION-LINE

Fenwick (1965) describes a variety of flat half-wave windings of small height, which are simple to manufacture and easy to deploy. They are essentially wound tranlines of $\lambda/2$ in total length and have a tuned input impedance. Bandwidths of about 0.2%, efficiencies up to 10% and impedances up to 6 ohms for $h \sim 0.01\lambda$ have been measured.



14. TRAILING ELECTRODE PAIR

For long range ELF reception in submarines, the antennas are necessarily electrically very small with very low signal to noise ratios. To reduce hull noise, the antennas take the form of tranline cables which are trailed through the water. Electrodes provide the earthing points into the sea-water (Burrows, 1978; Fessenden and Cheng, 1974). Because the antenna has an electric dipole pattern, nulls in coverage occur and helical loops have been considered to improve performance (Burrows, 1978 and Cafaro et al., 1974).

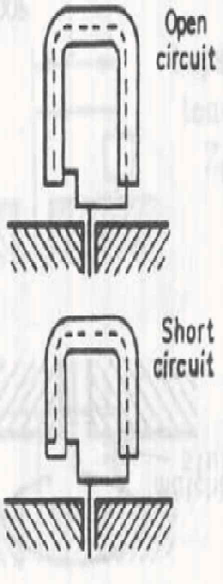
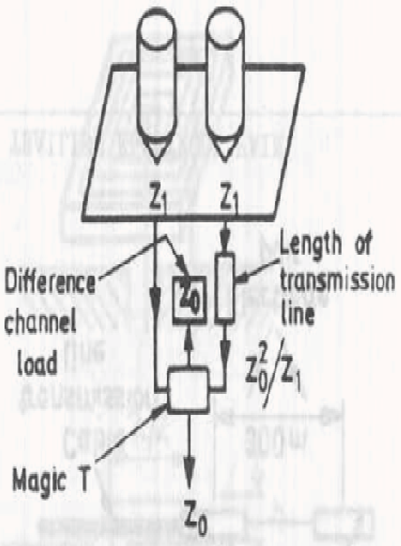


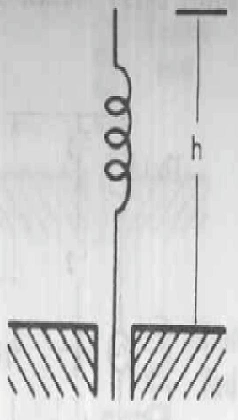
15. HULA-HOOP

The Hula-hoop was originally devised by Boyer (1963) and later analysed by Burton and King (1963) and Egashira (1975). Measurements by Boyer indicated that the antenna gain was only 2-3dB lower than a $\lambda/4$ mast at 4MHz and a good match was obtained by means of a stub. Egashira gives the radiation resistance as

$$r_r \sim 320\pi^2 (h/\lambda)^2$$

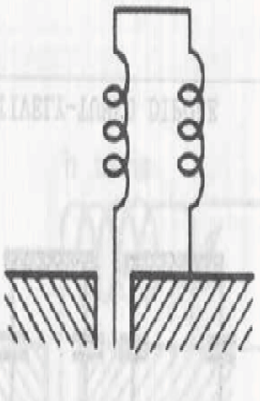
without the matching stub, which is twice that of the top-loaded monopole.

 16. DOUBLY-FED COAXIAL ANTENNA	This antenna consists of a doubly fed, air-cored coaxial line folded back upon itself, and is basically a transmission-line type. Only small height reductions are claimed (Rahman and Maclean, 1978) with input resistances comparable to that of a monopole of the same height. The short-circuit version is much more narrowband than the open-circuit version.
 17. ELECTRICALLY-SMALL COMPLEMENTARY PAIRS	The mutual coupling between two short, wide antennas can be used to obtain a wider bandwidth with a good VSWR but with a similar efficiency to that of a matched monopole (Schroeder and Soo Hoo, 1976). The impedances of the two antenna components are made complementary by an inversion network.



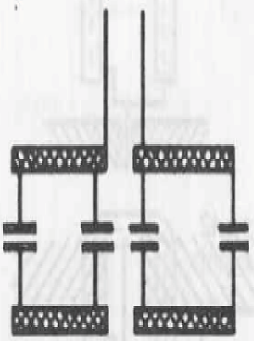
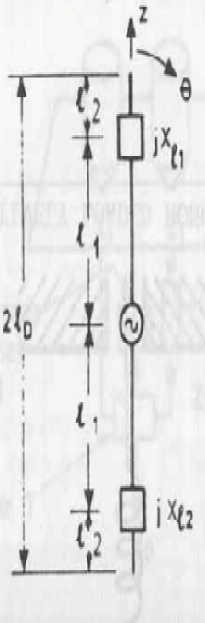
18. INDUCTIVELY LOADED MONOPOLE

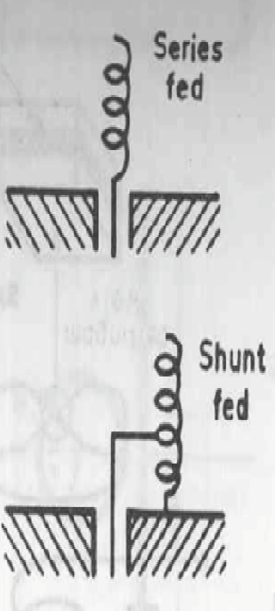
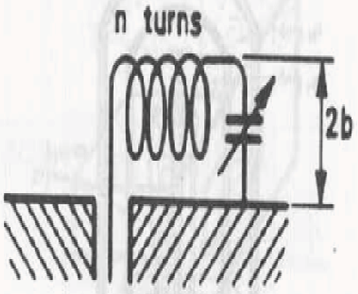
The inductively loaded monopole was first measured by Walters in 1954 and analysed more recently by Harrison (1963), Hansen (1973 and 1975) and Fujimoto (1968). There appears to be some advantage in positioning the inductor half-way along the monopole rather than at the base as in a tuning circuit (Fournier and Pomerleau, 1978). An efficiency of 50 -70% can be obtained for $h \sim 0.1\lambda$ and by choosing the Q of the coil, appropriately, the bandwidth can be increased to about 2% and the radiation resistance from 4 to 23 ohms (Goubau, 1976, p50).



19. FOLDED VERSION OF (18)

A folded version of the above has been suggested by Walters (1955) and gives a wider bandwidth and larger impedance by varying the ratio of the diameters of the two arms.

 20. CAPACITIVELY-TUNED DIPOLE	Lamensdorf (1973) has used capacitive tuning for a folded dipole over a band of 573-1270MHz. Diodes were chosen as capacitive components. No efficiency values were given.
 21. PATTERN CONTROL USING LOADED DIPOLES	The directionality and bandwidth of wire elements can be enhanced by synthesis, with the use of lumped or continuous passive loadings (Popovic, 1982; Tsunekawa et al. 1982). In the case of simple dipole elements, unidirectional patterns have been obtained from a loaded folded dipole (Mikuni and Nagai, 1972) and some beam shift, typically of the order of 35°, can be achieved. (Hirasawa and Fujimoto, 1980; Tsunekawa et al. 1983).

 22. HELIX	The helix can be made to resonate at a shorter length than the monopole provided that the total length of wire in the helix is about $\lambda/2$ (Weeks, 1968). The pattern is that of the electric dipole and the radiation resistance is typically that of a monopole of the same height. The impedance can be increased by a shunt feed or by a bifilar winding or by certain loading techniques (Hansen 1961; Ramsdale and Maclean, 1971). The efficiency in the VHF region has been analysed by Hiroi and Fujimoto (1976) showing that 80% can be achieved for a length of 0.05λ. Further analysis is given in Section 2.2 of this book.
 23. MULTI-TURN LOOP (MTL)	The MTL has a low radiation resistance $r_r \sim 320\pi^6 n^2 (b/\lambda)^4$ and relatively high ohmic losses, giving low efficiency and a high Q. The ohmic losses are affected by the proximity of the loops (Smith, 1972) and limit the radiation efficiency even if n is increased. Matching circuits reduce the efficiency even further. A MTL has been developed for HF shipboard applications, and the pattern was basically that of a horizontal magnetic dipole (Goubau, 1976, p10).

Dual-frequency PIFA

Two separate patches with a dual feed

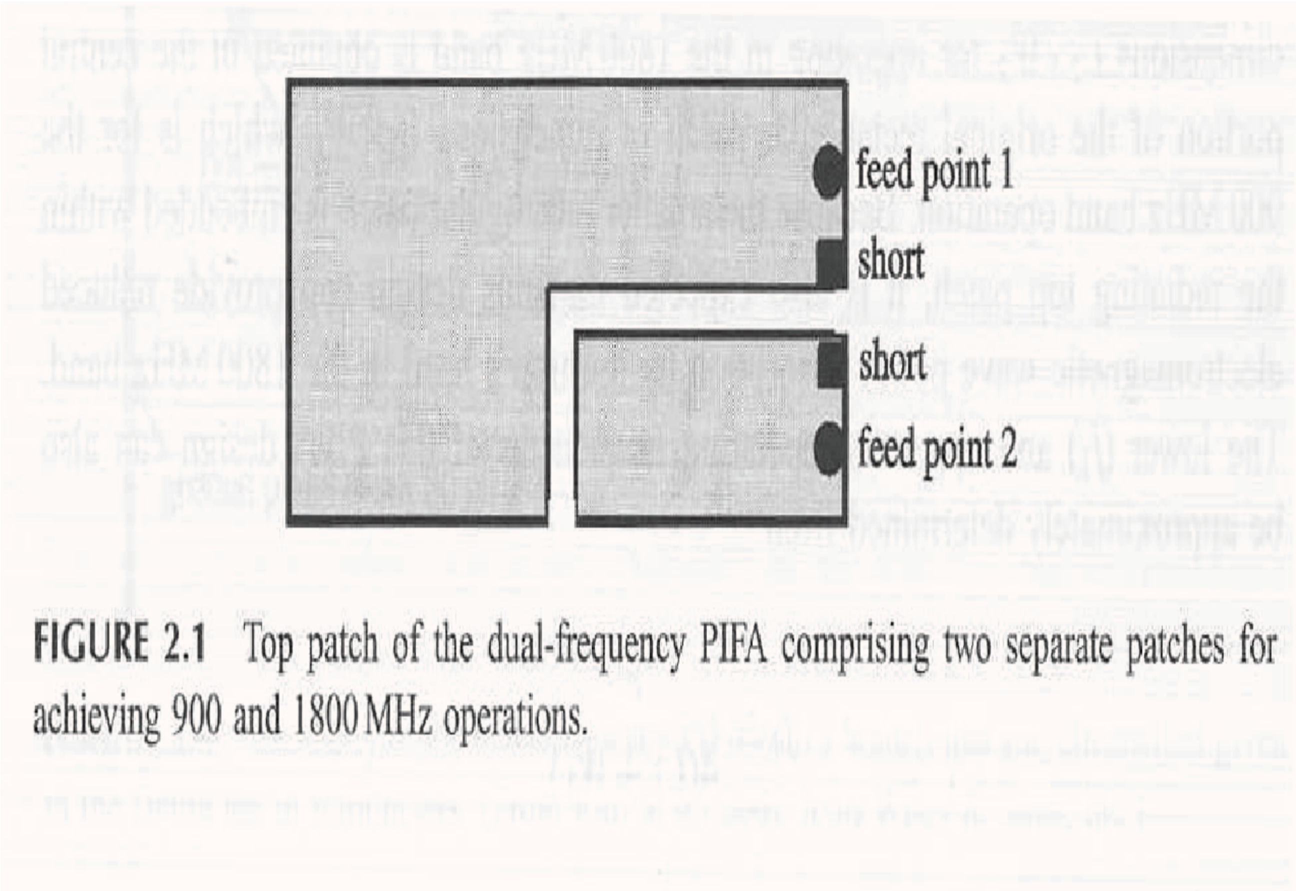


FIGURE 2.1 Top patch of the dual-frequency PIFA comprising two separate patches for achieving 900 and 1800 MHz operations.

Dual-frequency PIFA

Patch with an L-shaped or folded slit

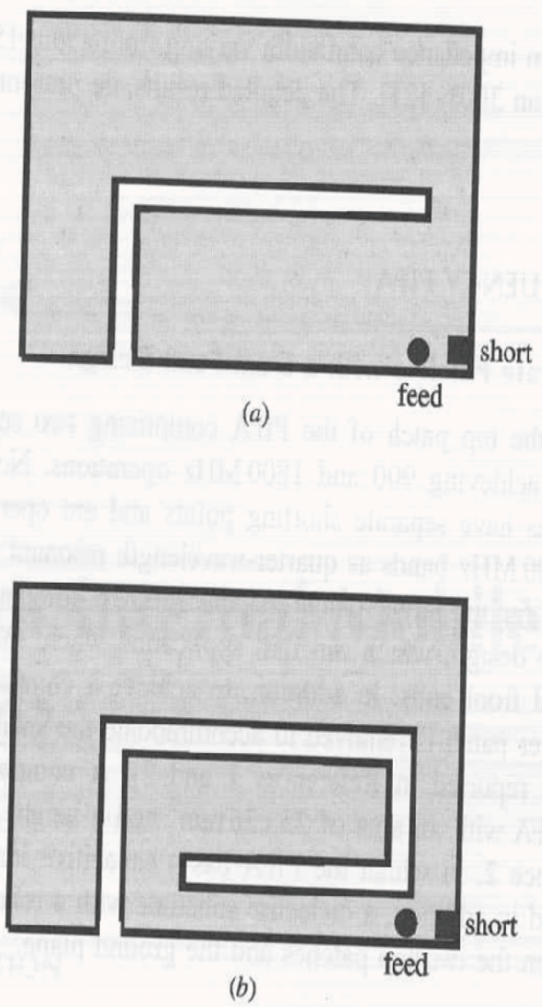


FIGURE 2.2 Top patch of the dual-frequency PIFA with (a) an L-shaped slit and (b) a folded slit.

Dual-frequency PIFA

Patch with a U-shaped slot

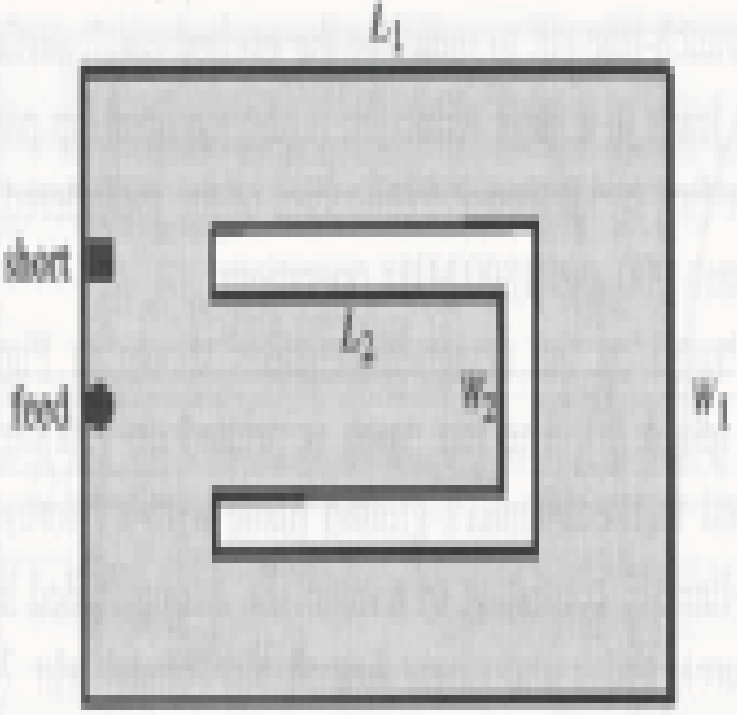


FIGURE 2.3 Top patch of the dual-frequency PIFA with an embedded U-shaped slot.

$$f_1 \approx \frac{c}{4(L_1+W_1)}, \qquad f_2 \approx \frac{c}{4(L_2+W_2)}$$

Dual-frequency PIFA

Patch with a branch line slit

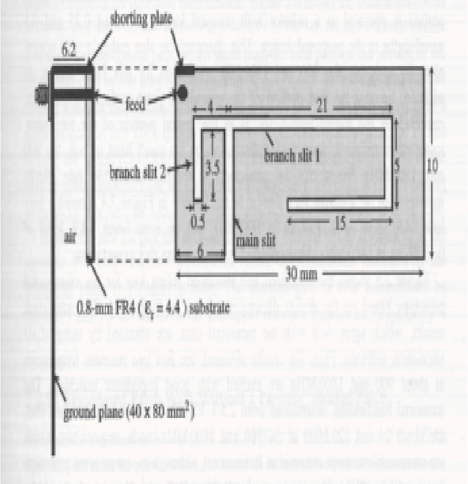


FIGURE 2.4 Geometry of the dual-frequency PIFA with a branch-line slit; dimensions given in the figure are in millimeters. (From Ref. 8, © 2002 John Wiley & Sons, Inc.)

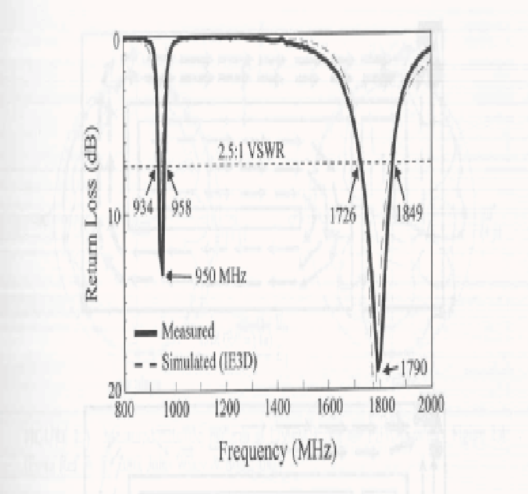


FIGURE 2.5 Measured and simulated return loss of the PIFA shown in Figure 2.4. (From Ref. 8, © 2002 John Wiley & Sons, Inc.)

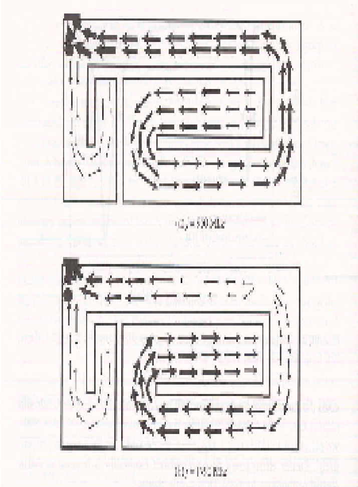


FIGURE 2.6 Simulated [illegible] surface current distributions (IE3D simulation results) at (a) f_L = 950 MHz and (b) f_H = 1790 MHz for the PIFA shown in Figure 2.4. (From Ref. 8, © 2002 John Wiley & Sons, Inc.)

$0.25\lambda/0.5\lambda$

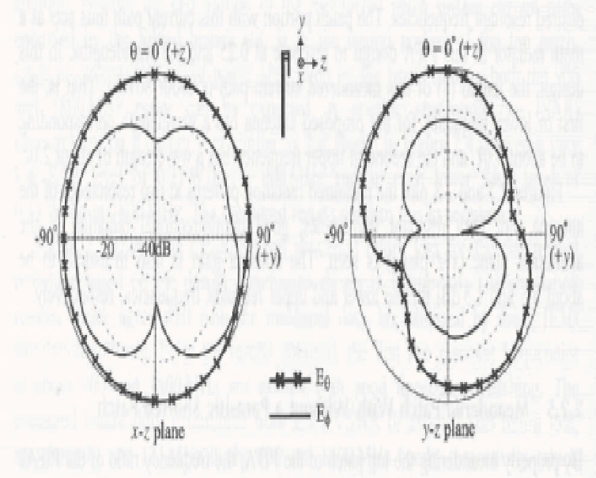


FIGURE 2.7 Measured radiation patterns at 950 MHz for the PIFA shown in Figure 2.4. (From Ref. 8, © 2002 John Wiley & Sons, Inc.)