Helical Antennas

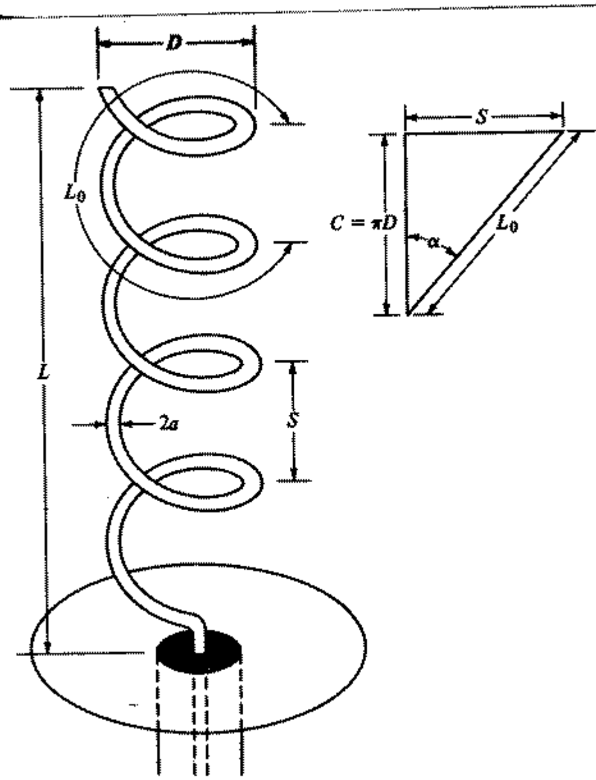


Figure 10.13 Helical antenna with ground plane. (Balanis)

→ John D. Kraus in 1946 at OSU developed

As shown, the geometry of a helical antenna is complicated and requires many parameters to describe. They are:

$D \equiv$ helix diameter (from wire center to center)

$C = \pi D$ – helix circumference

$S \equiv$ turn spacing (from wire center to center) $= L/N$

$\alpha \equiv$ pitch angle $= \tan^{-1}(S/\pi D)$ $\quad 0° < \alpha < 90°$

loop ↑ (at 0°), straight wire ↑ (at 90°)

$N \equiv$ # of turns

$L \equiv$ axial length (helix height) $= NS$

Helix parameters cont.

$2a \equiv$ diameter of helix conductor/wire

$L_0 \equiv$ length of one turn of wire $= \sqrt{(\pi D)^2 + S^2}$

↳ Obviously, total wire length $= NL_0 = L_n$

Sense – helix can be right-handed (RH) or left-handed (LH) [Thumb of correct hand points down helix, away from feed, and fingers curl in direction of helix]

Radiation Modes:

1) Normal mode – radiates broadside to helix in a fashion similar to a short dipole or small loop (occasionally used to replace monopoles)

2) Axial mode – radiates in direction of helix axis (most common)

3) Conical mode – radiates in a cone around axis of helix (not useful)

4) others – hybrids of prior 3 modes, can be multi-lobed, not useful

→ won't discuss 3) + 4) further

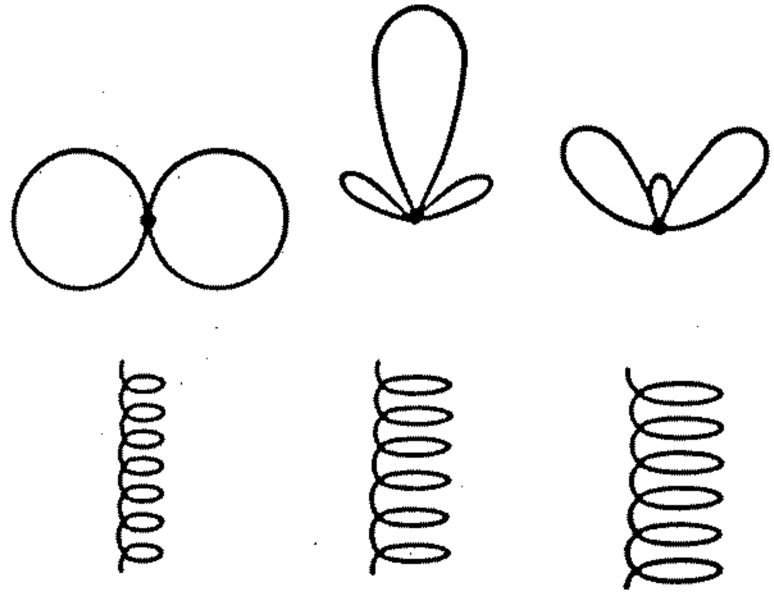
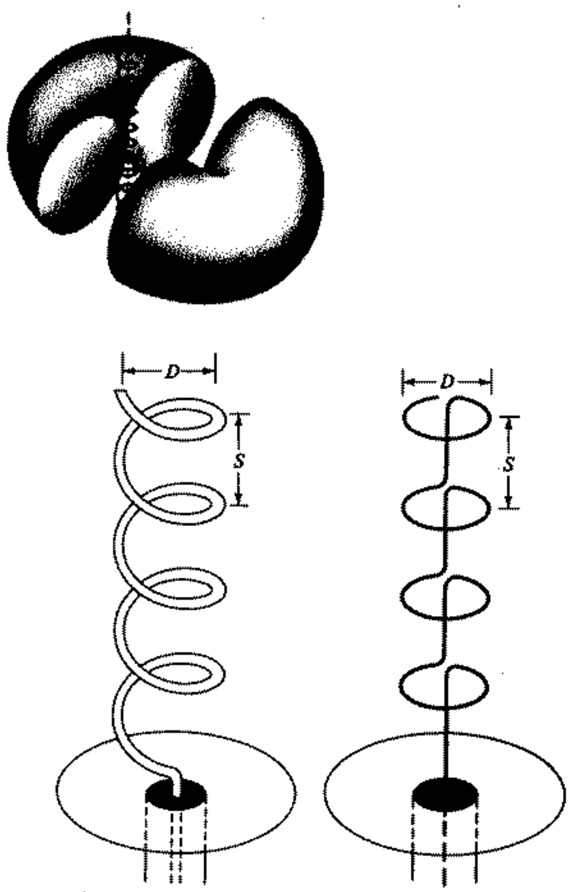


FIG. 13-1 Three radiation modes of a helical antenna. [Joy]

Normal Mode



(a) Normal mode (b) Equivalent

Figure 10.14 Normal (broadside) mode for helical antenna and its equivalent. (Balanis)

Normal Mode cont.

* As shown in Fig 10.14, the helix is usually operated over a ground plane and can be modeled as a series of N small loops and short dipoles.

* For normal mode operation, the helix dimensions must be small in terms of wavelengths

  i.e. $D \ll \lambda$ and $L_n = N L_0 \ll \lambda$
* narrow BW + low radiation efficiency (like short dipoles / small loops)
* Since the helix is small, we can assume the current is constant over the length of the helix and independent of # of turns (can encourage by proper termination of helix)

Dipole (short w/ length $l = S$ = helix spacing)

$$E_\theta = j\eta \frac{k I_0 S e^{-jkr}}{4\pi r} \sin\theta \quad \leftarrow \text{far-field}$$

Loop (small w/ radius $a = D/2$)

$$E_\phi = \eta \frac{k^2 (D/2)^2 I_0 e^{-jkr}}{4r} \sin\theta \quad \text{far-field}$$

Note: we have 2 orthogonal field components that are in time phase quadrature (90° out of phase) $\Rightarrow$ elliptical or circular polarization!

<u>Normal mode cont.</u>

To characterize the relative strengths of the E_θ + E_ϕ, we use the axial ratio

$$AR = \frac{|E_\theta|}{|E_\phi|} = \frac{\left(\frac{\eta k |I_0| S \sin\theta}{4\pi r}\right)}{\left(\frac{\eta k^2 (D/2)^2 |I_0| \sin\theta}{4r}\right)}$$

$|j| = 1$
$|e^{-jkr}| = 1$

$$\boxed{AR = \frac{4S}{\pi k D^2} = \frac{2S\lambda}{(\pi D)^2} = \frac{2S\lambda}{C^2}}$$

↳ we can manipulate/vary S + D to achieve essentially any AR (if the above eqn gives a # less than zero, it is $\frac{1}{AR}$ of a polarization ellipse, else it is the AR of a polarization ellipse)

<u>Wheeler coil/helix</u> (after H.A. Wheeler)

$AR = 1$ (<u>Circular polarization</u>, except at $\theta = 0°$ or $180°$ where there is no radiation)

occurs when $C^2 = (\pi D)^2 = 2S\lambda \rightarrow S = \frac{(\pi D)^2}{2\lambda}$

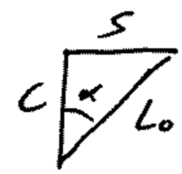
↳ $\boxed{C = \pi D = \sqrt{2S\lambda}}$

and so $\boxed{\alpha_{cp} = \tan^{-1}\left(\frac{S}{\pi D}\right) = \tan^{-1}\left(\frac{\pi D}{2\lambda}\right)}$

↑
circularly polarization

Normal Mode cont.

Alternatively, we can use Pythogorean's Rule on the right triangle of Fig. 10-13



$$L_o^2 = C^2 + S_{cp}^2 \qquad \Big\downarrow \text{sub } C = \sqrt{2S\lambda}$$

$$= 2S_{cp}\lambda + S_{cp}^2$$

$$S_{cp}^2 + 2S_{cp}\lambda + L_o^2 = 0 \qquad \Big\downarrow \text{apply quadratic eqn}$$

$$S_{cp} = \lambda\left[-1 \overset{\text{choose}}{\pm} \sqrt{1 + (L_o/\lambda)^2}\right]$$

$$\sin\alpha = \frac{S_{cp}}{L_o}$$

and

$$\boxed{\alpha = \sin^{-1}\left[\frac{-1 + \sqrt{1 + (L_o/\lambda)^2}}{(L_o/\lambda)}\right]}$$

ex.

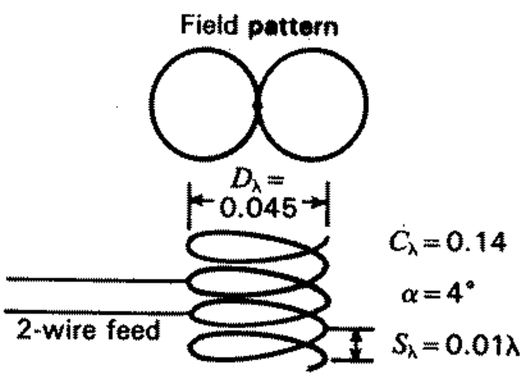


Figure 7-65 Resonant narrowband circularly polarized monofilar normal-mode Wheeler coil. Pattern is that of a short dipole.

[Kraus]

Normal mode cont.

α small $\rightarrow$ essentially loop operation w/ horizontal linear polarization (AR<<1)

$\alpha \rightarrow 90°$ $\rightarrow$ essentially dipole operation w/ vertical linear polarization (AR>>1)

$\Rightarrow$ The most common application of normal mode helices is as a compact substitute for a $\lambda/4$ monopole over a ground plane or the Normal Mode helix antenna (NMHA) AKA Resonant (quarter-wave) stub helix antenna

Set $L_n = NL_o = \lambda/4$ & $AR >> 1$ (nearly vertical linear)

Why? * Smaller/shorter than $\lambda/4$ monopole

* the inductive nature of a helix can offset (resonate) the capacitive nature of short dipoles.
* higher radiation resistance than a short dipole

$$R_r \simeq 640\left(\frac{L}{\lambda}\right)^2$$ where L is helix height

by comparison a short monopole has radiation resistance

$$R_r = 2R_{r_{1\,dipole}} = \frac{1}{2}\left[80\pi^2\left(\frac{L}{\lambda}\right)^2\right] = 395\left(\frac{L}{\lambda}\right)^2$$

(4-19) + (4-106)

Normal mode cont.

ex. Stub helix operating at $\lambda = 34\text{cm}$ ($f \simeq 883\,MHz$) w/ a specified height of $2\text{in} = 5.08$ cm and using 5 turns

$$L_n = \lambda/4 = N\sqrt{(\pi D)^2 + S^2} = N\sqrt{(\pi D)^2 + (L/N)^2}$$

$$\frac{34\text{cm}}{4} = 5\sqrt{(\pi D)^2 + \left(\frac{5.08\text{cm}}{5}\right)^2}$$

$$\underline{D = 0.43385\text{cm} = 0.01276\,\lambda}$$

$$\underline{S = \frac{5.08\text{cm}}{5} = 1.016\text{ cm} = 0.02988\,\lambda}$$

$$\alpha = \tan^{-1}\left(\frac{S}{\pi D}\right) = \tan^{-1}\left(\frac{1.016}{\pi(0.43385)}\right)$$

$$\underline{\alpha = 36.702°}$$

$$AR = \frac{2S\lambda}{(\pi D)^2} = \frac{2(1.016)(34)}{(\pi\, 0.43385)^2}$$

$\underline{AR = 37.2}$ ← nearly vertically linear

$$R_r \simeq 640\left(\frac{L}{\lambda}\right)^2 = 640\left(\frac{5.08}{34}\right)^2$$

$\underline{R_r \simeq 14.3\,\Omega}$ ← Not great but better than

$R_{r,\text{monopole}} = 395\left(\frac{5.08}{34}\right)^2 = 8.8\,\Omega$ & $\lambda/4 = 8.5\text{ cm}$

(helix 60% of length of monopole)

Axial Mode

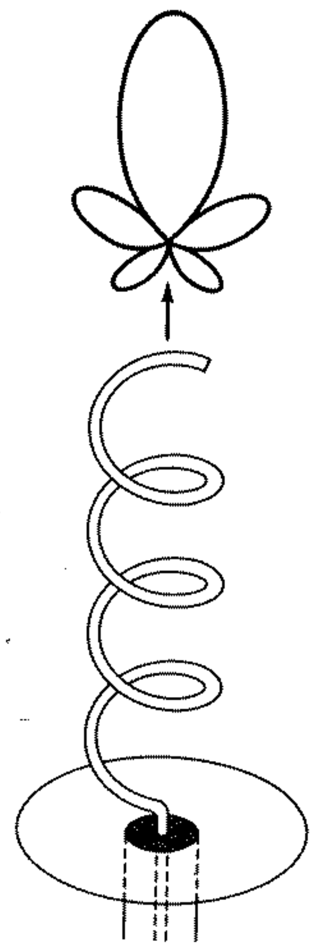


Figure 10.15 Axial (endfire) mode of helix. (Balanis)

→ can be thought of as an endfire array ("supergain") of loop antennas over a ground plane

→ radiates a circularly polarized wave

For axial mode:

* $C/\lambda \sim 1$ best $\quad 3/4 \lesssim C/\lambda \lesssim 4/3$ ← stays in axial mode

$1.\bar{7}$ to 1 BW!

* ↳ $D = C/\pi \sim 0.3\lambda$ (Diameter)

* Pitch angle α usually $12° < \alpha < 14°$ (near optimum)

* spacing $S \simeq \lambda/4$ $\quad \alpha = \tan^{-1}\left(\frac{S}{C}\right) = \tan^{-1}(0.25) = 14°$

→ S + α inter-related

Axial mode cont.

Notes:

* usually, use 4 or more turns, but axial mode operation possible w/ as few as 2 turns

* Directivity & gain directly related to number of turns

* Practically, gains up to ~18 dBi can be achieved (before losses start to greatly diminish further increases in gain)

* can be fed axially, peripherally, or via a tap connected along helix

* helix conductor size/shape not critical. Usually, circular/round wire used where $0.005 < \frac{2a}{\lambda} < 0.05$
* Current decays exponentially near feed, then forms traveling wave in middle section, small standing wave at end
* helix can be self-supporting, wound around a dielectric form, supported by a center post w/ radial supports, ... Using a dielectric form or pipe will shift the operating BW lower since $\epsilon_{eff} > \epsilon_0$
* usually helix used over a ground plane, but reflector rings or wire mesh grid have been used. Some examples are shown in Fig. 7-13

* Input impedance approximately/nearly resistive

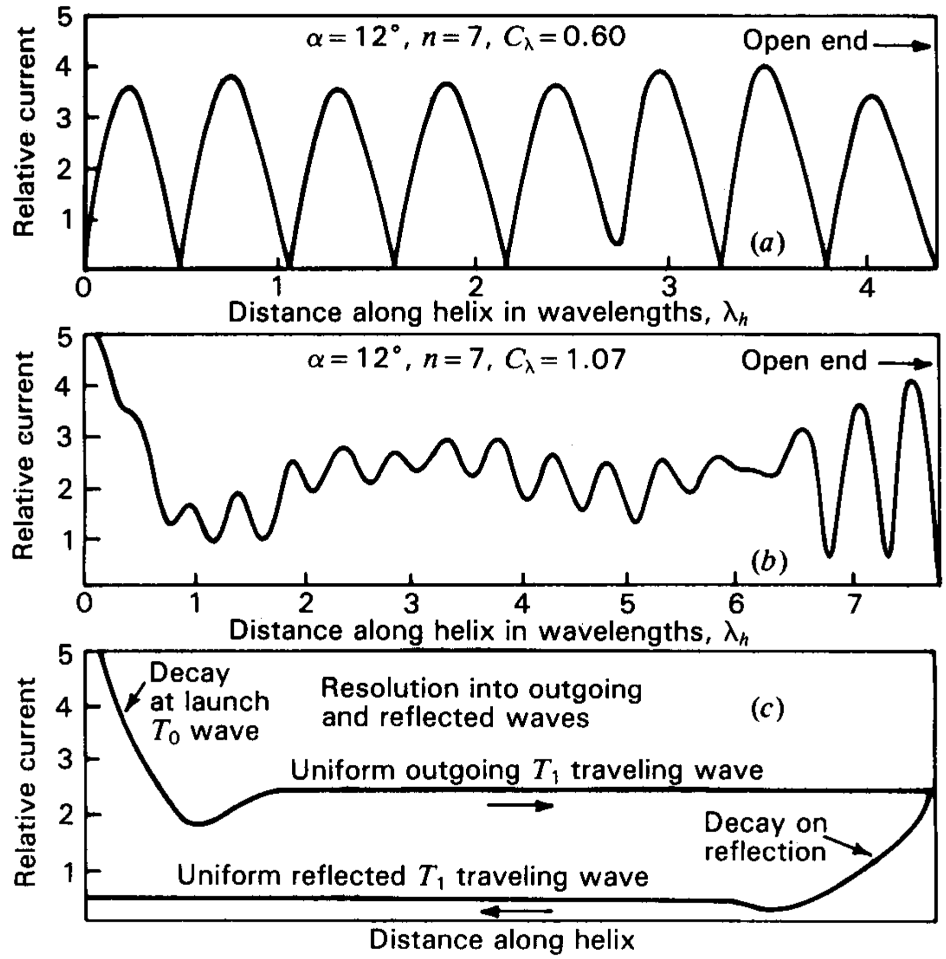


Figure 7-3 Typical measured current distribution (*a*) at a frequency below the axial mode of operation and (*b*) at a frequency near the center of the axial mode region. (*c*) Resolution of currents into outgoing and reflected waves. (*From Kraus and Williamson, "Characteristics of Helical Antennas Radiating in the Axial Mode,"* J. Appl. Phys., **19**, *87–96, January 1948.*) Compare with distribution on the long, thick cylindrical conductor in Fig. 9-18. [From Antennas (2nd Edition) by Kraus]

- Note the standing wave current distribution for the helical antenna when operating at a frequency below the axial mode (top picture).

- When the helical antenna is operating in the axial mode (middle picture), note how the current magnitude initially falls exponentially near the feed (launching the axial mode radiation), stabilizes into a relatively constant traveling wave distribution in the middle of the helix, and has a standing wave current distribution near the open end of the helix.

Axial mode cont

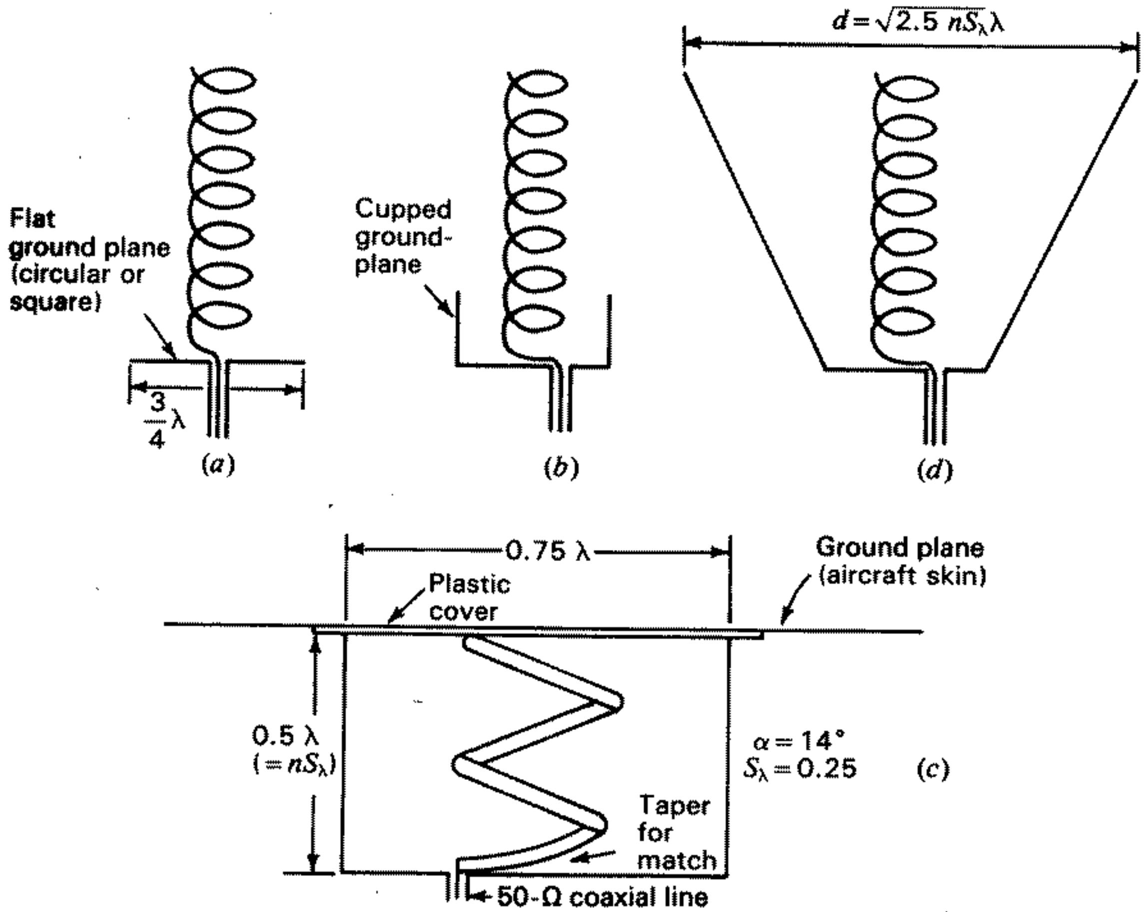


Figure 7-13 (*a*) Monofilar axial-mode helical antenna on flat ground plane and (*b*) in shallow cupped ground plane (see also Fig. 7-16c). (*c*) General-purpose flush-mounted 2-turn monofilar axial-mode helical antenna with taper feed for matching to a 50-Ω coaxial line (*after Bystrom and Bernsten, ref. 1, p. 277*) (see also Fig. 7-16*a* and *b*). (*d*) Deep conical ground-plane enclosure for reducing side and back lobes. (*After K. R. Carver, ref. 2, p. 277*).

Kraus, Antennas (2nd)

Axial Feed input resistance (empirical)

$$\boxed{R = 140 \, C/\lambda \pm 20\%}$$

Peripheral Feed input resistance (empirical)

$$\boxed{R \simeq \frac{150}{\sqrt{C/\lambda}} \pm 10\%}$$

* Good for $N \geq 4$, $0.8 \leq C/\lambda \leq 1.2$, + $12° \leq \alpha \leq 14°$

Axial mode cont.

Over the usual $3/4 < C/\lambda < 4/3$ range, we can thus have

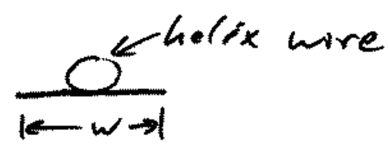
$$100 \lesssim R_{axial} \lesssim 190\,\Omega$$

$$130 \lesssim R_{peripheral} \lesssim 175\,\Omega$$

This presents a problem as we usually will drive a helix through a ground plane w/ a coaxial transmission line.

Options:

A) Taper last 1/4 turn of helix to gradually make it parallel to ground plane w/ a dielectric slab of height h and relative permittivity ϵ_r used as a spacer (see Figure 7-16) where the helix tubing is either flattened to a width w or the helix conductor is soldered to a flat plate / metal strip of width w.



$$h = \frac{w}{\left(\frac{2}{\sqrt{\epsilon_r}\, Z_0}\right) - 2}$$

Axial Mode cont.

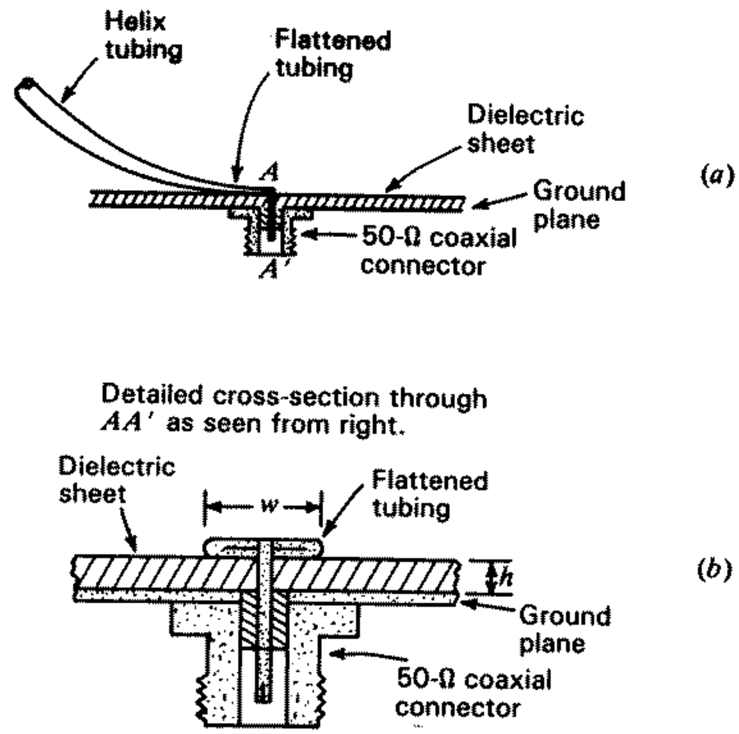
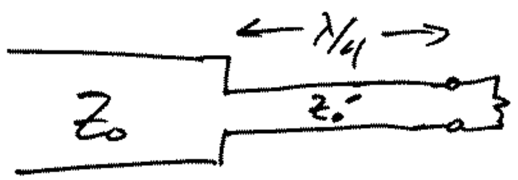


Figure 7-16 (*a*) Gradually tapered transition from helix to coaxial line with detailed cross section at (*b*).

Kraus, Antennas (2nd)

B) Another possibility (w/ peripheral feed) is to use a $\lambda/4$ transformer or another type of microstrip impedance transformer

← at center frequency



← helix input resistance

$$Z_0' = \sqrt{Z_0 Z_L}$$

Both options will decrease the BW of the helix (wrt VSWR or impedance being acceptable)

Axial Mode cont.

Radiation Pattern + Beamwidth

→ Rather than input impedance / VSWR, the factor that limits the useful frequency range of the axial-mode helical antenna is the radiation pattern. This is illustrated in Fig 7-19.

← Normal mode   conical mode →

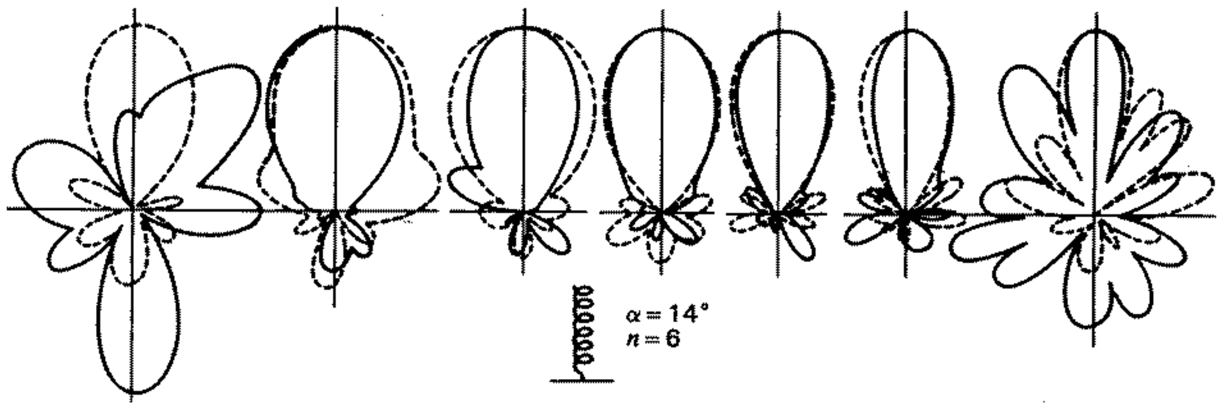


Figure 7-19 Measured field patterns of monofilar axial-mode helical antenna of 6 turns and 14° pitch angle. Patterns are characteristic of the axial mode of radiation over a range of circumferences from about 0.73 to 1.22λ. Both the circumference and the frequency (in megahertz) are indicated. The solid patterns are for the horizontally polarized field component (E_ϕ) and the dashed for the vertically polarized (E_θ). Both are adjusted to the same maximum. (*After Kraus.*) Kraus, Antennas (2nd)

Note: The radiation pattern is characteristic of the axial mode for $0.73 \lesssim C/\lambda \lesssim 1.22$

From empirical measurements by Kraus et al in 1948-49 time frame

$$\boxed{HPBW\,(\text{deg}) = \frac{52\,\lambda^{3/2}}{C\sqrt{NS}}}$$ Half-power Beamwidth

$$\boxed{FNBW\,(\text{deg}) = \frac{115\,\lambda^{3/2}}{C\sqrt{NS}}}$$ First-Null Beamwidth

Axial mode cont.

Fig 7-21 illustrates what happens to the HPBW wrt C/λ as well as NS & N

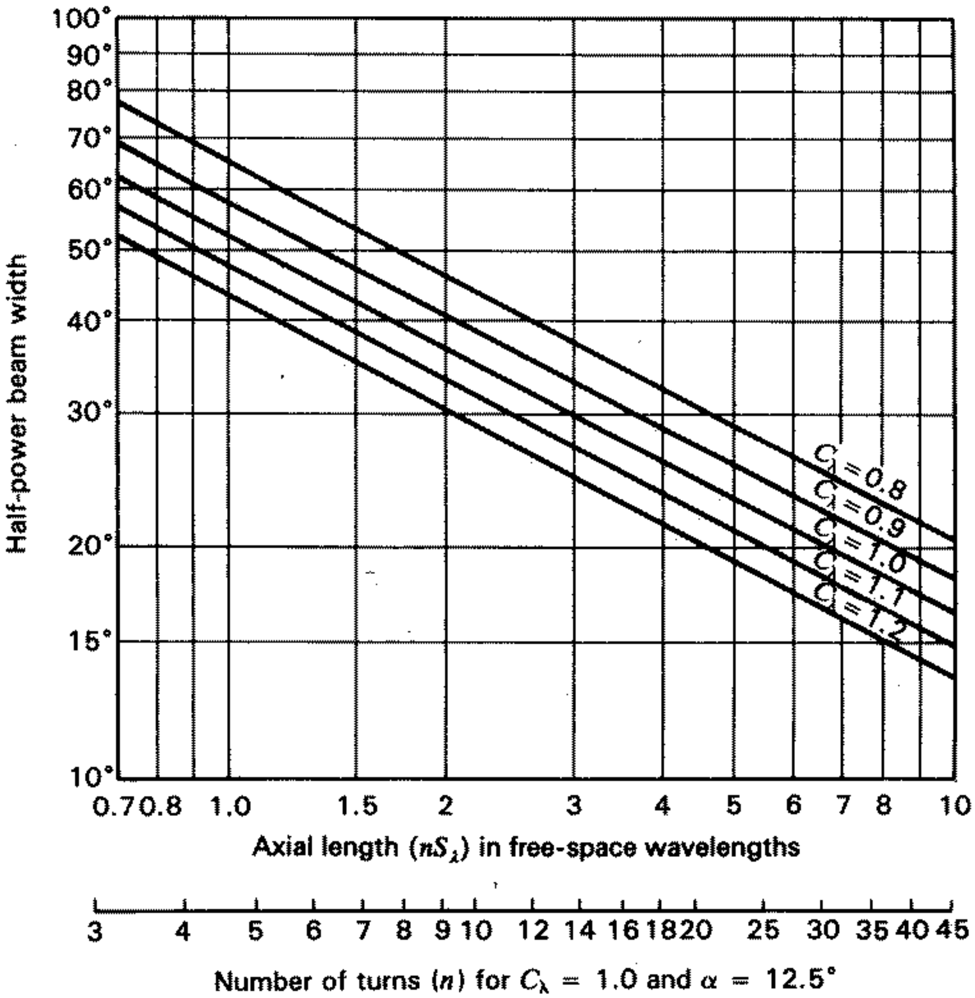


Figure 7-21 Half-power beam width of monofilar axial-mode helical antenna as a function of the axial length and circumference in free-space wavelengths and also as a function of the number of turns for $C_\lambda = 1.0$ and $\alpha = 12.5°$ (lower scale). (*After Kraus.*) Kraus, Antennas (2nd)

Directivity

→ closely related to the HPBW is the directivity

In Chap 2, we had the approx. $D_o \simeq \dfrac{41,253}{\theta_{1d}\,\theta_{2d}}$

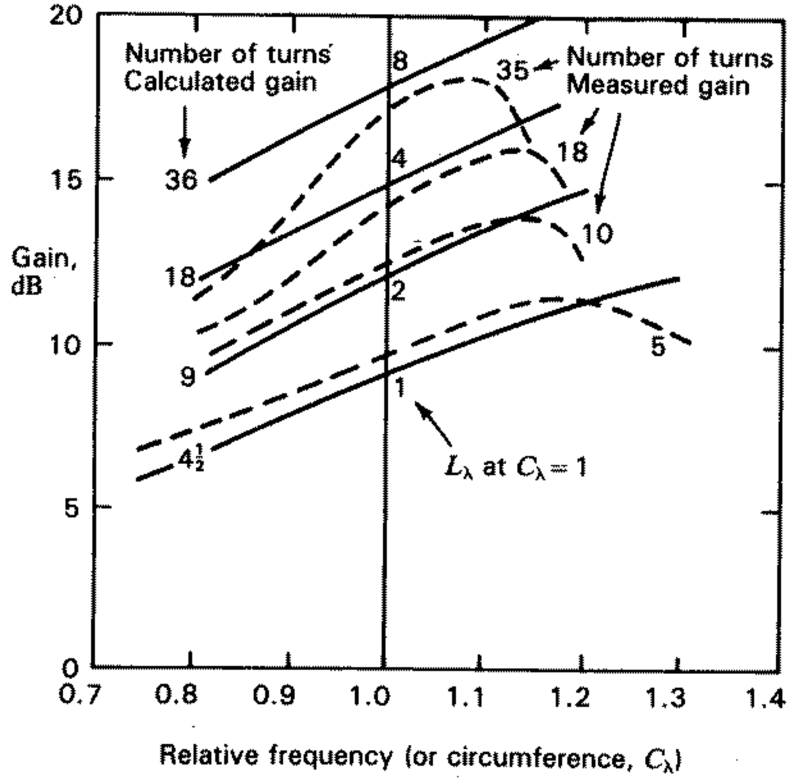
which, using the HPBW eqn, leads to

$$D_o \simeq 15 N \frac{C^2 S}{\lambda^3} \quad \text{(dimensionless)}$$

However, according to Kraus, a better approx. is

$$\boxed{D_0 \simeq 12N \frac{C^2 S}{\lambda^3} \quad \text{(dimensionless)}}$$

to account for the effects of side lobes & other radiation pattern shape details. Fig 7-22 illustrates the above eqn. as well as measured gains



Assume $G \simeq D$ for axial mode helices.

Figure 7-22 Measured (dashed) gain curves of monofilar axial-mode helical antennas as a function of relative frequency for different numbers of turns for a pitch angle of $\alpha = 12.8°$. (*After H. E. King and J. L. Wong, "Characteristics of 1 to 8 Wavelength Uniform Helical Antennas,"* IEEE Trans. Ants. Prop., **AP-28**, *291, March 1980*.) Calculated (solid) gain curves are also shown for different numbers of turns. Kraus, Antennas (2nd)

Notes:
- → get higher gains/directivities w/ bigger N
- → trade-off narrower bandwidth
- → peak measured gain at $C/\lambda = 1.1$ to 1.2
- → measured results tended to be 1dB low due to how exp. helices were built

Axial mode cont.

Axial Ratio (AR)

→ measure of how good the circular polarization is considered to be on axis

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

as Illustrated below in Fig 7-38 for $N=7$

The equations for HPBW, FNBW, D_o, R, + AR are good for $12° < \alpha < 14°$, $N > 3$, + $0.8 \le C/\lambda \le 1.15$ (Kraus)

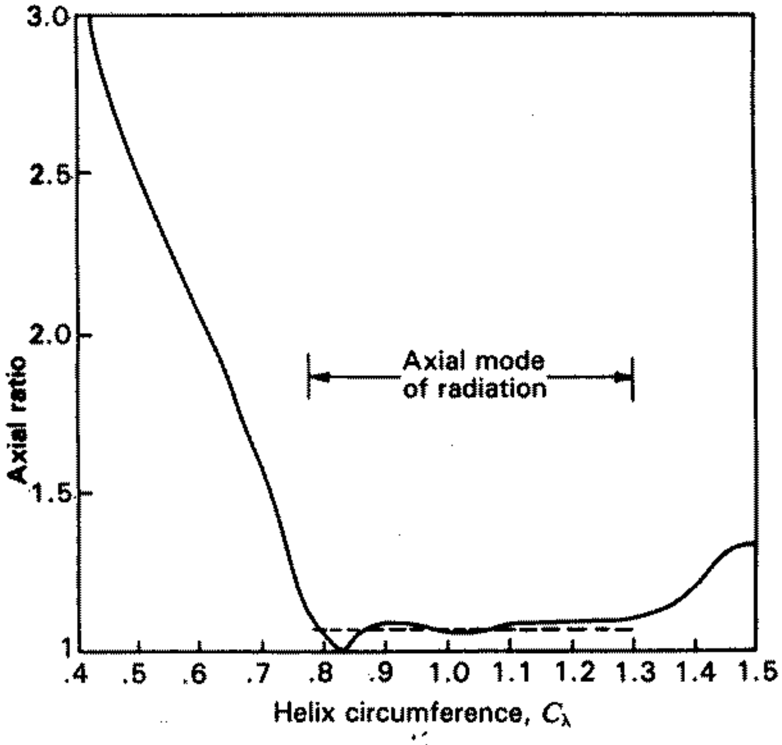
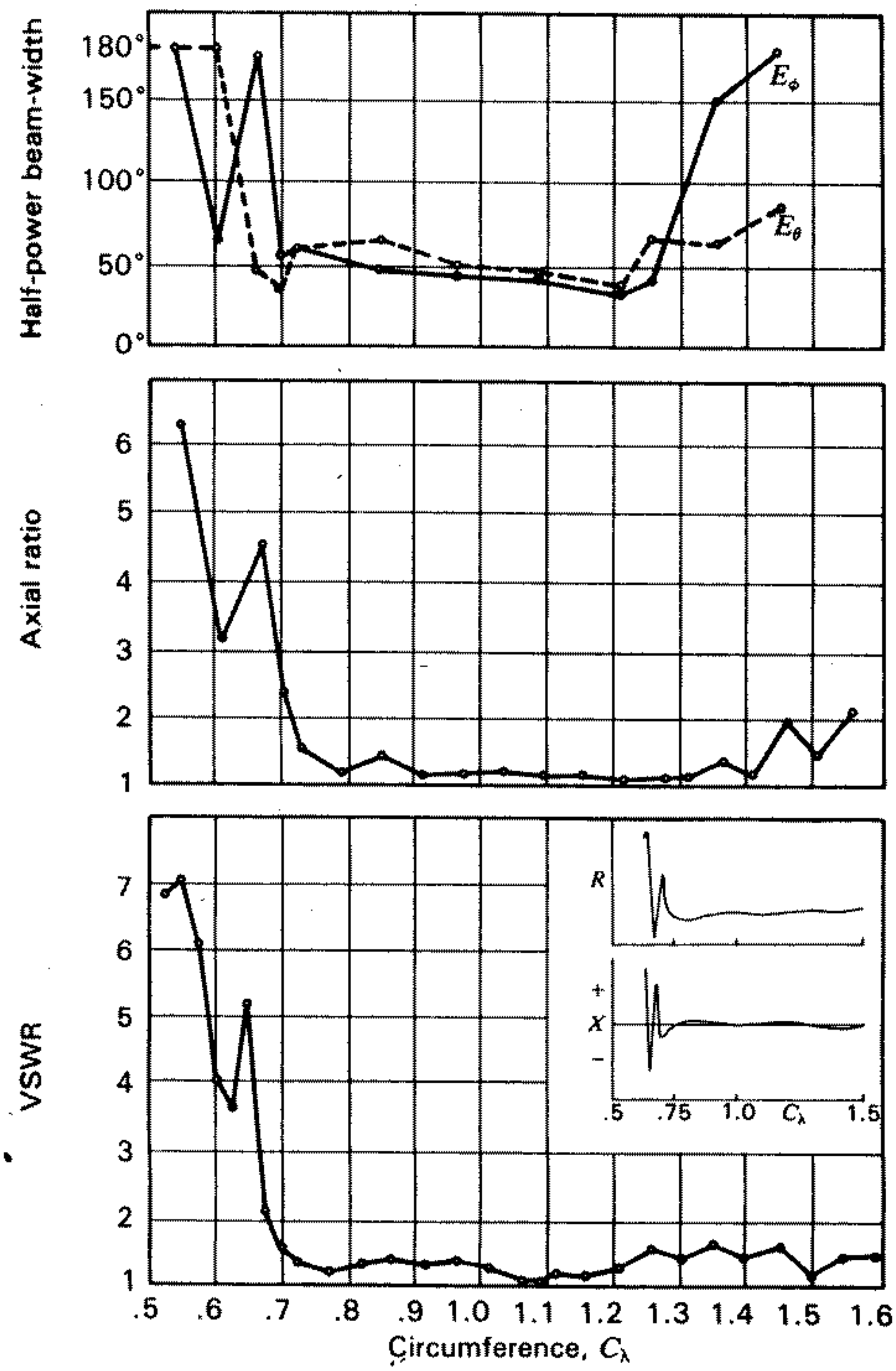


Figure 7-38 Axial ratio as a function of helix circumference C_λ for a 13°, 7-turn monofilar axial-mode helical antenna. The dashed curve is from (17). (*After Kraus.*)

Kraus, Antennas (2nd)

Fig 7-23 shows the HPBW, AR, VSWR, R, + X for a $N=6$, $\alpha = 14°$ helical antenna

Axial Mode cont.



← nearly constant in axial mode

← ~0 in axial mode

Figure 7-23 Summary of measured performance of 6-turn, 14° monofilar axial-mode helical antenna. The curves show the HPBW for both field components, the axial ratio and the VSWR on a 53-Ω line as a function of the relative frequency (or circumference C_λ). Trends of (relative) resistance R and reactance X are shown in the VSWR inset. Note the relatively constant R and small X for $C_\lambda > 0.7$. (*After Kraus.*)

Kraus, Antennas (2nd)

Axial Mode cont.

* Fig 7-39 shows how the helix dimensions relate to various performance attributes (Z, AR, Rad. Pattern)
* To get good overall performance, do an "AND" operation
* Good conditions: AR < 1.25, R ≃ constant + real, Rad Patt. → Axial mode
* Optimum α chosen for maximum bandwidth $12° \lesssim \alpha \lesssim 14°$

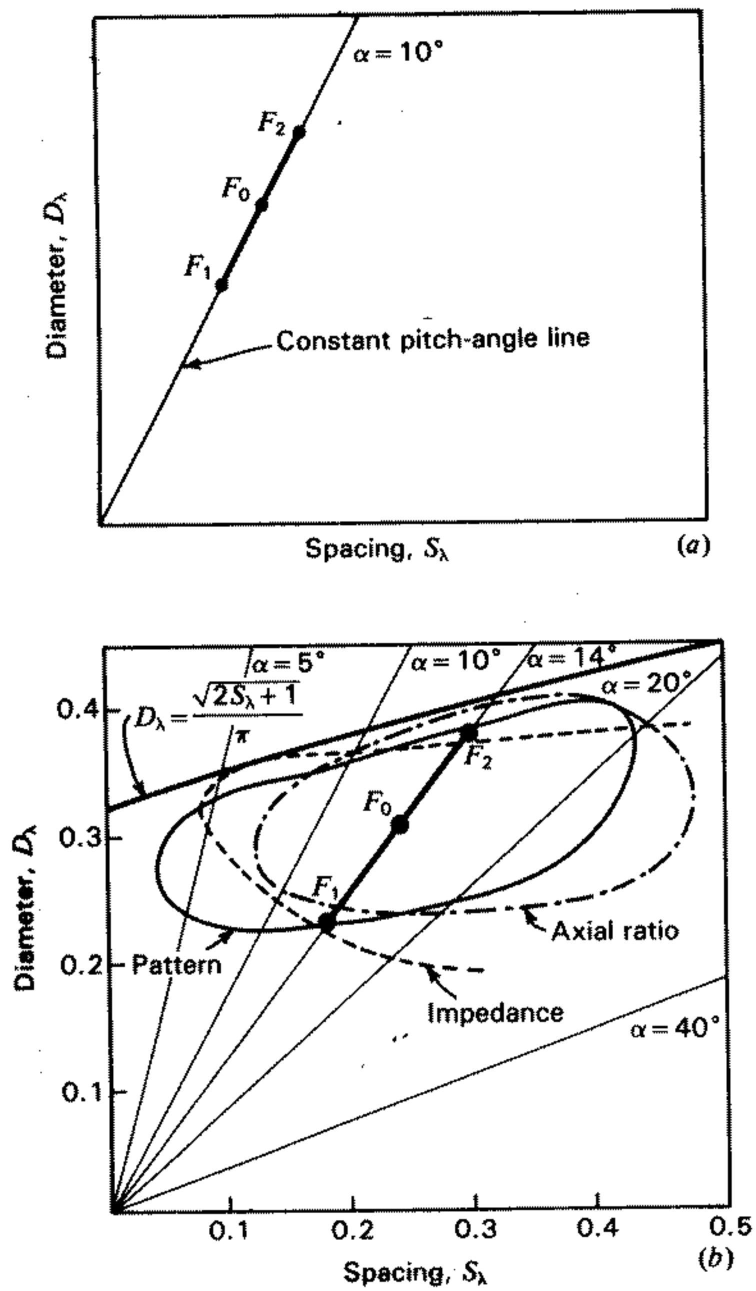


Figure 7-39 Diameter-spacing charts for monofilar helices with measured performance contours (b) for the axial mode of radiation.

Kraus, Antennas (2nd)

Axial Mode cont.

ex. Say that a helix is constructed w/ the following dimensions: $L = 1m$, $D = 15\,cm$, and $N = 9$

Analyze some properties of this helix.

$$\alpha = \tan^{-1}\left(\frac{S}{\pi D}\right) \quad \text{where} \quad \underline{S = L/N = 1/9\ m}$$

$$= \tan^{-1}\left(\frac{1/9}{\pi(0.15)}\right) \qquad S/\lambda_c = \frac{1/9}{0.47124} = 0.2358$$

$$\underline{\alpha = 13.2672^\circ}$$

Axial mode (@ center freq) $\quad C \sim \lambda_c = \pi D = \pi(0.15) = 0.47124\,m$

$$f_{center} = c/\lambda = \frac{2.998 \times 10^8}{0.47124} = \underline{\underline{636.2\ MHz}}$$

Est. low freq. $\quad f_{Low} \simeq 0.75 f_c = 477\ MHz$

Est. high freq. $\quad f_{high} \simeq 1.3 f_c = 827\ MHz$

$\Rightarrow$ UHF TV Band!

@ f_c $$HPBW = \frac{52\lambda^{3/2}}{C\sqrt{NS}} = \frac{52(0.47124)^{3/2}}{\pi\, 0.15\sqrt{9(1/9)}} = \underline{\underline{35.7^\circ}}$$

$$FNBW = \frac{115\lambda^{3/2}}{C\sqrt{NS}} = \frac{115(0.47124)^{3/2}}{\pi\, 0.15\sqrt{9(1/9)}} = \underline{\underline{78.9^\circ}}$$

$$D_o = 12N\frac{C^2 S}{\lambda^3} = 12(9)\frac{(0.15\pi)^2(1/9)}{(0.47124)^3} = \underline{25.465}$$

$$= \underline{\underline{14.06\ dBi}}$$

$$AR = \frac{2N+1}{2N} = \frac{2(9)+1}{2(9)} = \underline{\underline{1.05}}$$

Applications of Helical Antennas

→ space communications, often helix used to feed parabolic dish

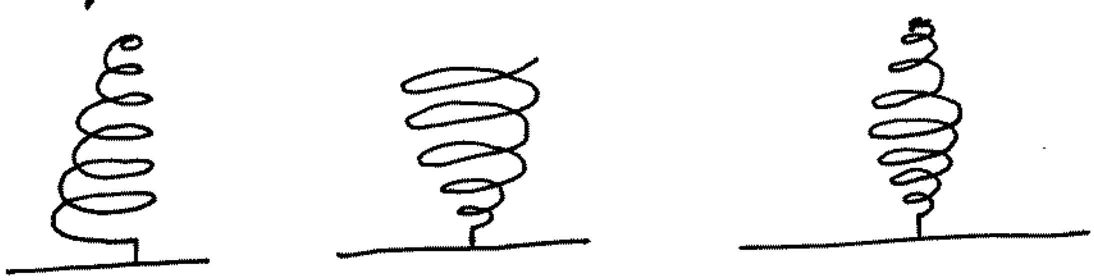
→ radio telescope

→ arrays (low cross talk)

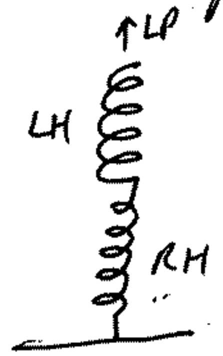
→ can be used as a parasitic element or lens to change polarization from linear to circular etc.

Variations on Helical Antenna

→ tapered helix for wider bandwidth



→ directive linear polarized antenna



→ No ground plane helix