8.5. EFFECTS OF ANTENNA HEIGHT

Since wavelengths are large at low and medium frequencies and hence it becomes difficult rather impracticable to use an antenna of resonant length. The vertical antennas at these frequencies are very much short. This has many interesting results as discussed below.

8.5.1. *Antenna Top Loading and Tuning.* The actual antenna height should be atleast quarter wavelength, above ground to make it resonant but when it is possible then its effective height should corresponds to $\lambda/4$. When an antenna is not of resonant length for given operating frequency its input impedance contains a reactive component. A grounded antenna of height of less than $\lambda/4$ has an input impedance containing a capacitive-reactance component. If the antenna height is between $\lambda/4$ and $\lambda/2$ its input impedance contains an inductive reactance component. Such system may be made resonant by adding lumped reactance (inductive or capacitive) of suitable magnitude and size as shown in Fig. 8.10.

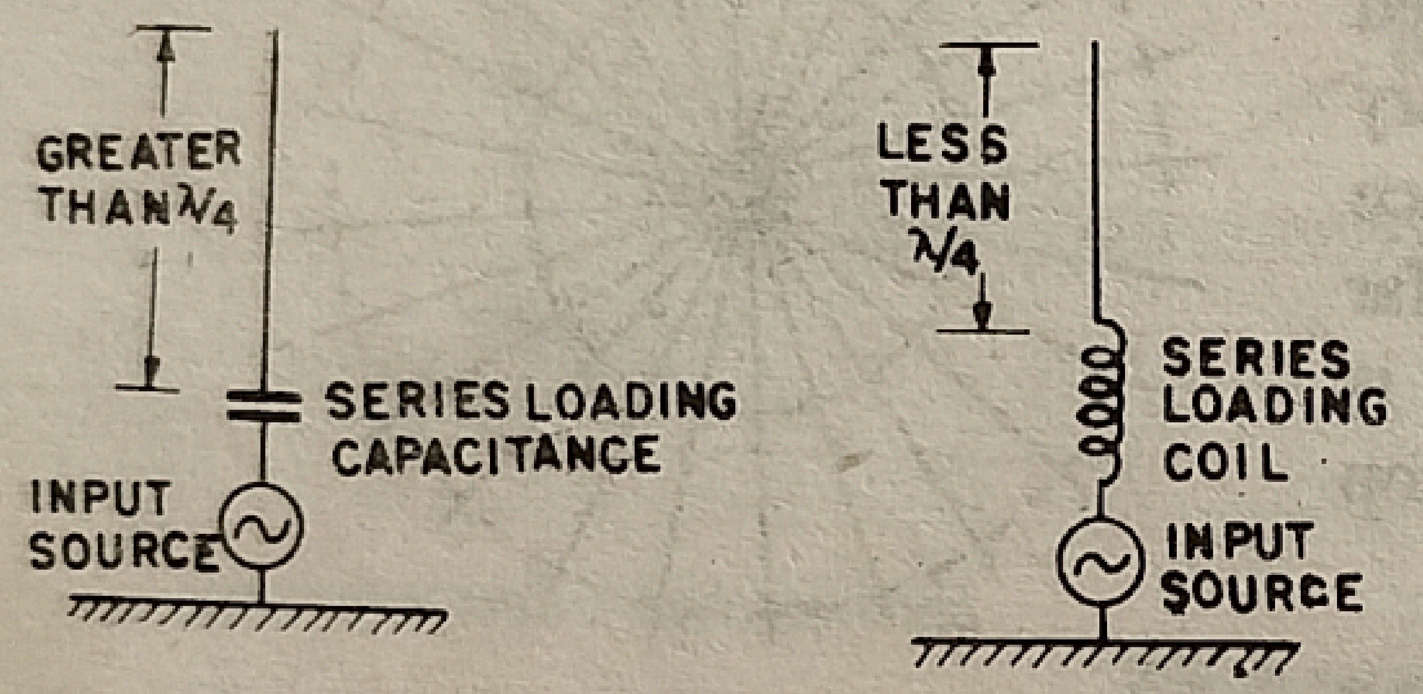


Fig. 8.10. Shows use of series loading coil or capacitance to attain the resonant length $\lambda/4$.

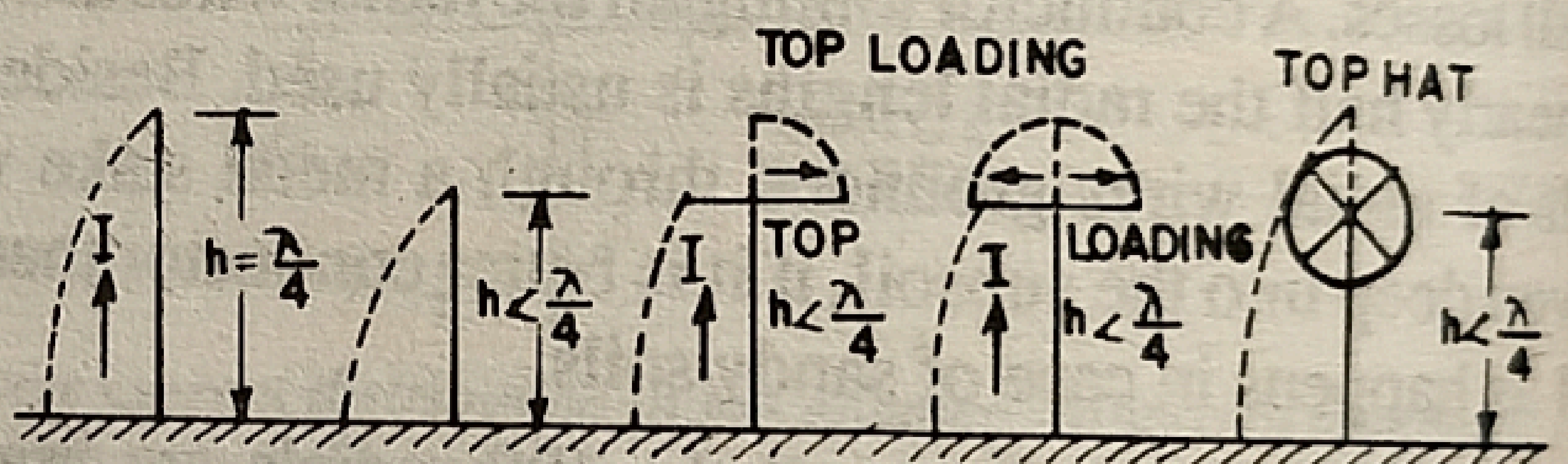


Fig. 8.11. Various form of top loading with current distributions (dotted lines).

Thus the grounded vertical antennas can be lengthened by adding inductance and shortened by adding series capacitance. The series inductive or capacitive reactance and made equal to that of capacitive and inductive reactances presented by the vertical radiator so that the impedance is resistive only at the resonant frequency. However, *radiation efficiency is sacrified by this way as series inductance or capacitance add to loss resistance and there is no improvement in the radiation resistance*. Antenna radiation efficiency can be increased by increasing radiation resistance of the system. "*Top loading*" is the answer for this. Top loading is a method to increase the effective capacitance at the top of the antenna. This is accomplished by mounting one or more horizontal conductors at the antenna top as shown. Top loading may assume the form of a inverted *L* or *T* or top hat as shown. By effecting top loading the current at the base of the antenna is increased and current distribution becomes more uniform.

The current in the horizontal portion is smaller than in vertical portion, therefore, antenna still works as vertically polarized antenna. The resulting current distribution along the vertical portion is similar to that as if extra vertical section is added. Thus the current along the upper portion of the vertical antenna increases and so also the radiation resistance and radiation efficiency.

Lumped reactances may also be used to maintain a resonant condition in an antenna system if the associated transmitter is operated under different frequencies. Thus a series inductor or capacitor connected with the vertical antenna may also serve as an antenna *tuning circuit*. These tuning element too reduces a little the radiation efficiency.

8.5.2. *Physical Height and Effective Height of an Antenna.* When a conductor of finite diameter is used as a radiator it usually behaves electrically as if it was taller than its physical height. Effective *electrical*

8.29. RECEIVING ANTENNAS

Although the characteristics determining qualities of an antenna system are the same as those determining its radiating properties, a practical receiving antenna is often much simpler in construction than its transmitting counterpart. At frequencies of the order of 2 MHz and lower, adequate amounts of energy pickup are usually obtainable with an antenna consisting of a short length of vertically oriented wire grounded at one end. At higher frequencies directive receiving antennas, such as an array, a *V*-antenna, or a rhombic antenna may be employed. The directional receiving properties of these antennas are identical with their directional properties as radiators. At operating frequencies of the order of 1000 MHz or higher, such as might be used in a point to point communication system, the same type of antenna is ordinarily used for transmitting and receiving both.

The basic function of a receiving antenna is to abstract energy from the passing electromagnetic wave radiated by a transmitting antenna. Thus antennas used for reception of radio waves are called receiving antennas. Because of the reciprocal relations between receiving and transmitting antennas, an antenna will have the same gain and directional characteristics when used as transmitting or as receiving antennas. However, one basic difference lies in the transmitting and receiving antennas is the power handling capacities. While a transmitting antenna is normally designed for large power transmission, the receiving antenna is meant for dealing with only smaller power of the order of few micro Watts. Hence the practical receiving antennas are usually, much simpler in construction than its counterpart transmitting antennas.

9.15. FREQUENCY INDEPENDENT ANTENNAS

9.15.1. *Condition For Frequency Independence* It was pointed out by V.H. Rumsey that the performance of a lossless antenna is independent of frequency, if its dimensions in terms of wavelength remain constant. Such a result could be achieved if the antenna could be specified in terms of angles. It was showed by Rumsey that this requirement would be fulfilled by any antenna whose equation in spherical co-ordinates is of the form

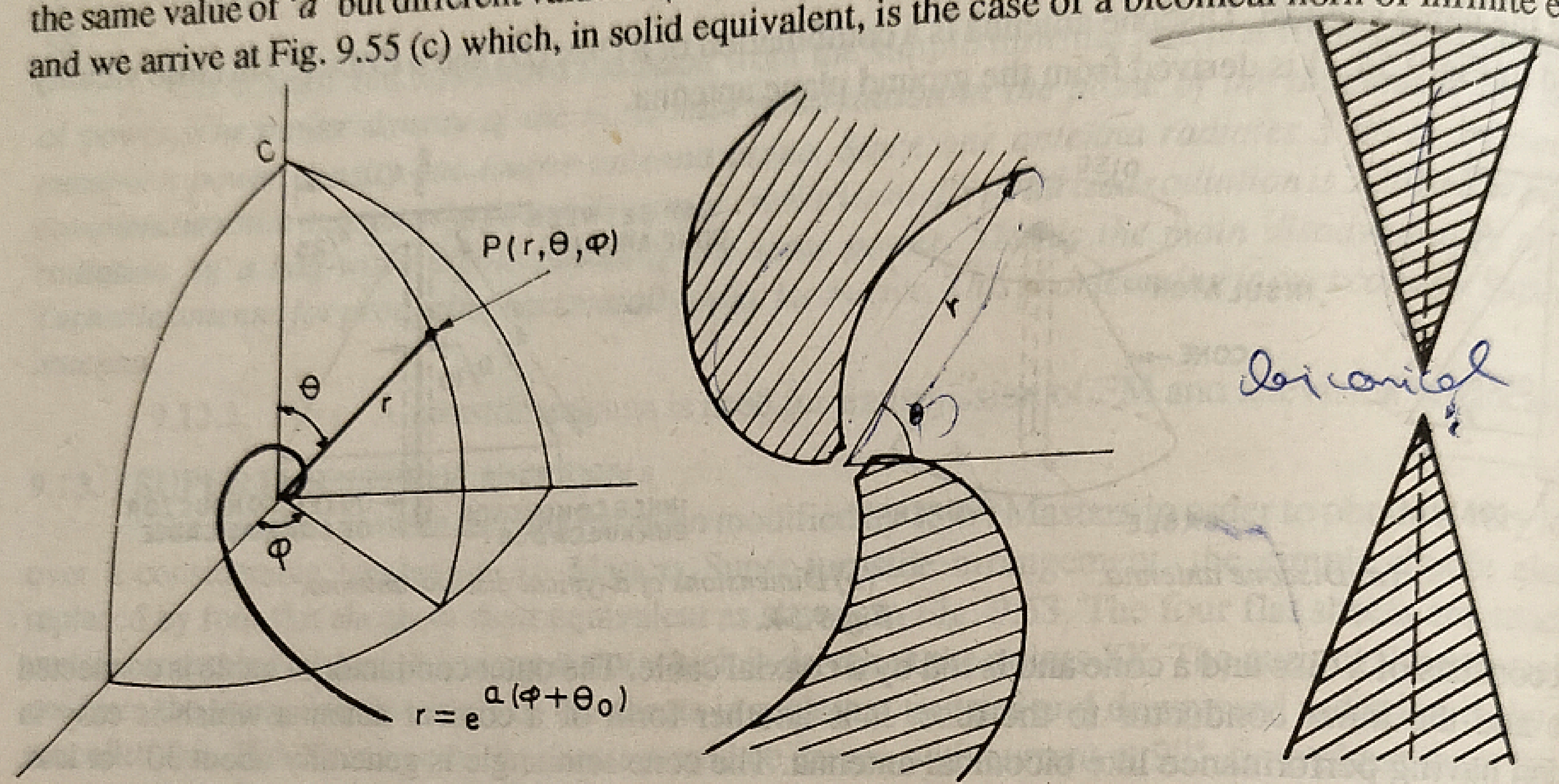
$$\boxed{r = e^{a(\varphi + \varphi_0)} f(\theta)}$$

where $f(\theta)$ is any function of θ [Fig. 9.55 (a)]. In case of planar antenna the equation reduces to

$$\boxed{r = e^{a(\varphi + \varphi_0)}} \qquad r = e^{a(\phi + \phi_0)} \qquad (9.95)$$

This is equation of an equiangular or logarithmic spiral where a is the rate of expansion and φ_0 the orientation.

In practice, however, the inner parts of the spiral must be terminated at a feed point of finite size and the outer parts terminate at some maximum radius. These terminations limit the highest and lowest frequencies of operation. A spiral of constant thickness does not strictly fulfil the conditions. Furthermore, a balanced feed point is needed and hence we are led to the configuration shown in Fig. 9.55 (b), where the four edges have the same value of 'a' but different value of φ_0. As 'a' tends to infinity, the spirals degenerate into straight lines and we arrive at Fig. 9.55 (c) which, in solid equivalent, is the case of a biconical horn of infinite extent.



(a) Coordinate system for antenna based on equiangular spiral, (b) Two symmetrical arms of flat spiral antenna. (c) Two asymetrical arms with $a \to \infty$. A biconical antenna is obtained if rotated about the common axis.

Fig. 9.55. Spiral antennas.

The radiation from a spiral antenna may be viewed as originating predominantly from the first resonance which occurs where the mean circumference is equal to a wavelength. It is then easy to appreciate that the pattern remains the same at all frequencies. Furthermore *one sees that the essential feature is roughly circular current flow* — a condition which is not fulfilled in the degenerate case of Fig. 9.55 (c), where flow is axial. In fact, the biconical antenna does not provide a constant pattern inspite of the fact that the input impedance converges to a constant value with increasing frequency.

The above principle led to the construction of equiangular spiral antennas and as per Rumsey, in order to, obtain frequency independent working, *an antenna should be specifiable in terms of angles.*

9.15.2. *General analysis of frequency independent antenna.* The analytical theory of frequency independent antennas is presented here which is due to V.H. Rumsey and simplified by Elliot for three dimensional configuration.

Consider an antenna, with both terminals indefinitely close to the origin of a spherical co-ordinate system, being symmetrically disposed along $\theta = 0, \pi$ axes. It is assumed that the antenna is perfectly conducting and is surrounded by an infinite homogeneous and isotropic medium. Let the surface of this antenna is described by

$$r = F(\theta, \varphi) \quad \text{... (9.96)}$$

where r is the distance along the surface or the edge. Suppose that one wishes to scale this antenna to a new frequency that K times lower than the original frequency. The antenna must, then, be made K times bigger to maintain the same electrical dimensions. Thus the new surface of this antenna is described by

$$r' = KF(\theta, \varphi) \quad \text{... (9.97)}$$

where K depends neither on θ nor on φ. The new and old surfaces are identical *i.e.* not only they are similar but congruent also (if both surfaces are infinite). Congruence can be established only by rotation in φ. Translation is not allowed because the terminals of both surfaces are at the origin. Rotation in θ is barred because both pairs of terminals are symmetrically disposed along the $\theta = 0, \pi$ axes. Hence for the second antenna to achieve congruence with the first, it must be rotated by an angle C so that

$$KF(\theta, \varphi) = F(\theta, \varphi + C) \quad \text{... (9.98)}$$

The angle of rotation C depends on K but neither depends on θ nor φ. Physical congruence implies that the original antenna would electrically behave the same at both frequencies. However, the radiation pattern will be rotated azimuthally through an angle C. For unrestricted value of K ($0 \le K \le \infty$) the pattern will rotate by angle C in φ with frequency, because C depends on K, but its shape will be unaltered. *Hence, the impedance and pattern will be frequency independent.*

If $0 \le K \le \infty$ holds, the nature of the function $F(\theta, \varphi)$ can be deduced form eqn

$$KF(\theta, \varphi) = F(\theta, \varphi + C) \quad \text{.... (9.99)}$$

differentiating w.r.t. the angle C we have

$$\frac{d}{dC}[KF(\theta, \varphi)] = \frac{d}{dC}[F(\theta, \varphi + C)]$$

$$\frac{\partial}{\partial C}[K][F(\theta, \varphi)] = \frac{\partial}{\partial(\varphi + C)}[F(\theta, \varphi + C)] \quad \text{... (9.100)}$$

Now differentiating eqn. 9.99 w.r.t. φ, we have

$$\frac{\partial}{d\varphi}[KF(\theta, \omega)] = \frac{\partial}{\partial\varphi}[F(\theta, \varphi + C)]$$

$$\frac{\partial}{d\varphi}[KF(\theta, \varphi)] = \frac{\partial}{\partial(\varphi + C)}[F(\theta, \varphi + C)]$$

or

$$K\frac{\partial}{\partial\varphi}[F(\theta, \varphi)] = \frac{\partial}{\partial(\varphi + C)}[F(\theta, \varphi + C)] \quad \text{... (9.101)}$$

Since RHS of eqn. 9.100 and 9.101 are equal so equating we have

$$\frac{\partial[K]}{\partial C}[F(\theta, \varphi)] = K\frac{\partial}{\partial\varphi}[F(\theta, \varphi)]$$

or

$$\frac{\partial(K)}{\partial C} \cdot r = K \cdot \frac{\partial r}{\partial\varphi} \quad | \because \text{By eqn. 9.96 } r = F(\theta, \varphi)$$

or ..

$$\boxed{\frac{1}{K}\frac{\partial(K)}{\partial C} = \frac{1}{r}\frac{\partial r}{\partial\varphi}} \quad \text{... (9.102)}$$

Since L.H.S. of eqn. 9.102 is independent of θ and φ, a general solution for the surface $r = F(\theta, \varphi)$ of the antenna is

$$r = F(\theta, \varphi) = e^{a\varphi} f(\theta) \quad \text{... 9.103 (a)}$$

where

$$a = \frac{1}{K}\left(\frac{\partial K}{\partial C}\right) \quad \text{... 9.103 (b)}$$

and

$a \equiv$ Parameter.

$f(\theta) =$ completely arbitrary function.

Eqn. (9.103) was first derived by V.H. Rumsey and it is the central result of the analysis. Hence, for any antenna to have frequency independent characteristics, its surface must be described by eqn. (9.103). This can be accomplished by specifying the function $f(\theta)$ or its derivatives. Several important classes of frequency independent antennas are identified from the above eqn.

9.15.3. *Frequency independent planar equi-angular spiral antennas.* The equiangular spiral is one geometrical configuration whose surface can be described by angles. It fulfills all the requirements for shapes that can be used to design frequency independent antennas. As a curve along its surface extends to infinity, it is necessary to designate the length of the arm to specify a finite size antenna. The lowest frequency of operation occurs when the total arm length is comparable to the wavelength and for all frequencies above this, the pattern and impedance characteristics are frequency independent.

9.15.4. *Planar spiral.* The shape of the equi-angular plane, spiral curve can be derived by choosing the derivative of $f(\theta)$ of eqn. 9.103 as follows *i.e.*

$$\boxed{f'(\theta) = \frac{df}{d\theta} = A\,\delta(\pi/2 - \theta)} \qquad \text{... (9.104)}$$

where A = An arbitrary positive constant.

δ = Dirac δ function.

Now using eqn. 9.104 from eqn. 9.103 we have

$$r = e^{a\varphi} f(\theta)$$

Let $$A = r_0 e^{-a\varphi_0} = \text{A positive function.} \qquad \text{... 9.105 (a)}$$

and $$\{r\}_{\theta = \pi/2} = r = \begin{cases} A e^{a\varphi} & \text{when } \theta = \pi/2 \\ 0 & \text{when } \theta \neq \pi/2 \end{cases} \qquad \text{... 9.105 (b)}$$

Then $$r = e^{a\varphi} \cdot A = e^{a\varphi} \cdot r_0 e^{-a\varphi_0}$$

$$r = r_0 e^{a(\theta - \varphi_0)} \quad \text{when } \theta = \pi/2 \qquad \text{.. 9.106 (a)}$$

$$r = 0 \quad \text{when } \theta = 0 \qquad \text{.. 9.106 (b)}$$

This is the equation of an equi-angular or logarithmic spiral *where a is the rate of expansion and φ_0 is the orientation.*

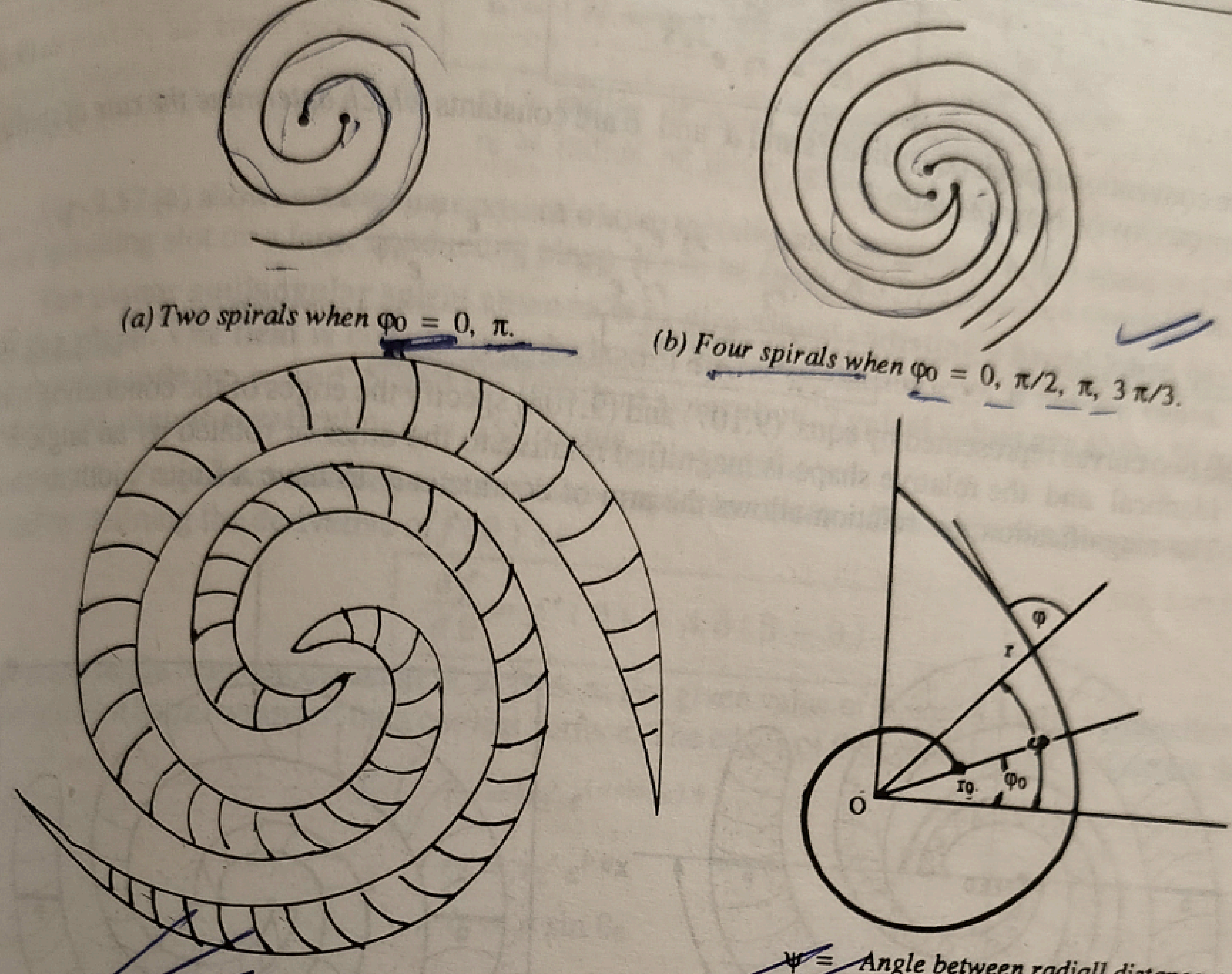
As the parameter A is arbitray, it follows that in eqn. (9.106) r_0 can be considered as fixed with φ_0 playing the role of a parameter. If φ_0 is given the values 0 and π, the antenna shown in Fig. 9.56 (a) results. If φ_0 is allowed to take on the values 0, $\pi/2$, π and $3\pi/2$, four spirals as shown in Fig. 9.56 (b) are formed with several symmetrical possibilities for connecting the terminals. Numerous other combinations are also possible.

If now φ_0 is allowed to take all values from 0 to φ_1 and all values from π to $\pi + \varphi_1$, an antenna of the type shown in Fig 9.56 (c) arises, where φ_1 is an arbitrary. It is clear from these examples that the varieties of possible combinations for the planar spiral case is seen to be endless. In the ideal theoretical analysis resulting in eqn. 9.100, the antenna shapes shown in Fig. 9.56 are assumed to be infinite. However investigation of the current distribution on such antennas reveals that the principal part of the excitation occurs in a resonant region around $r = \lambda/2$. Hence when the planar spiral antennas of Fig. 9.56 are truncated at some finite size, one can anticipate that the antenna should perform satisfactorily down to a frequency at which the wavelength is comparable to the antenna size.

An upper frequency limit may be expected when the actual antenna terminals no longer behave as a pair of points infinitesimally apart at the origin. Experiments confirm these frequency limits. In interesting feature of the planar spiral antenna is that Babinet principle is applicable to it. With reference to Fig 9.56 (c).

Let Z_1 = Input impedance of the antenna for a value $\varphi_1 = \alpha$

and Z_2 = Input impedance of the antenna for a value $\varphi_1 = \pi - \alpha$



(a) Two spirals when $\varphi_0 = 0, \pi$.

(b) Four spirals when $\varphi_0 = 0, \pi/2, \pi, 3\pi/3$.

(c) Spiral plate.

ψ = Angle between radiall distance r and the tangent to the spiral

(d) Single Spiral

Fig. 9.56 Some simple shapes of frequency independent planar antennas.

then the two antennas form complementary screens and hence as usual

$$Z_1 Z_2 = \frac{\eta^2}{4}$$

For a special case when $\varphi_1 = \pi/2$

$$Z_1 = Z_2$$

then

$$Z_1^2 = \frac{\eta^2}{4} \equiv Z_2^2$$

and

$$Z_1 = Z_2 = \frac{\eta}{2} \qquad \because \eta = 120\,\pi$$

188.4 Ω

and

$$Z_1 = Z_2 = 60\,\pi$$

and

$$Z_1 = Z_2 = 188.4 \quad \text{ohms.}$$

The experimentally measured value of input impedance is 164 ohms and theoretical value is 188.4 ohm. The difference is due to the finite arm length, finite thickness of the plate and non-ideal feeding conditions. This self-complementary feature was first pointed out by Mushiake.

An equiangular or logarithmic spiral metallic solid surface, designated as P, can be created by defining the curves of its edges from eqn. 9.105 (b) as

$$\boxed{r_2 = r_2' \, e^{a\varphi}} \qquad \text{... (9.107)}$$

or

$$r_3 = r_3' \, e^{a\varphi}$$

$$r_3 = r_2' \, e^{-a\delta} \cdot e^{a\varphi}$$

$$r_3 = r_2' e^{a(\varphi - \delta)} \quad \text{... (9.108)}$$

or

$$r_3' = r_2' e^{-a\delta} \quad \text{... (9.109)}$$

where

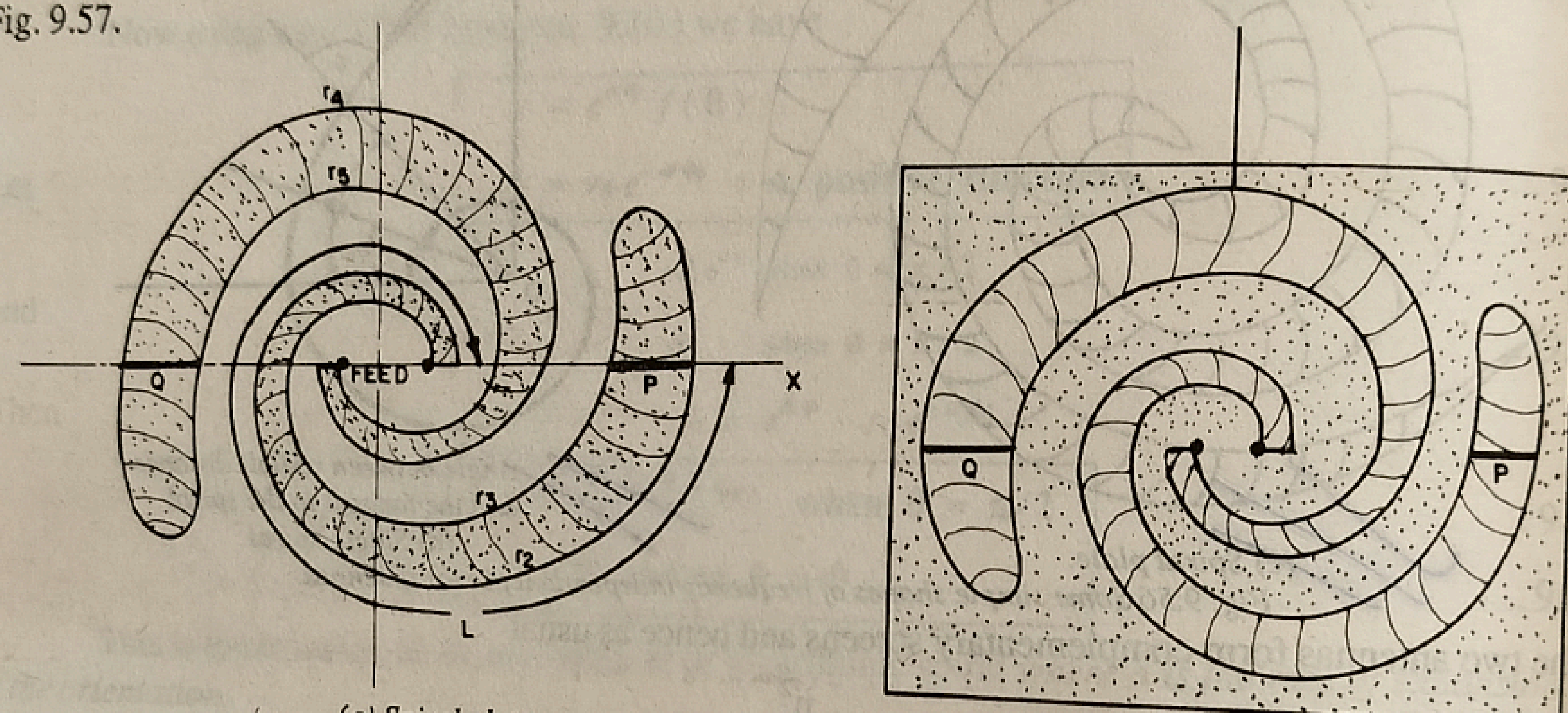
r and φ are conventional polar co-ordinates and a and δ are constants *which determine the rate of spiral and arm width respectively*. Now the ratio K

$$K = \frac{r_3}{r_2} = \frac{r_2' e^{a(\varphi - \delta)}}{r_2' e^{a\varphi}} = \frac{e^{a\varphi} \cdot e^{-a\delta}}{e^{a\varphi}}$$

or

$$K = e^{-a\delta} < 1 \quad \text{... (9.110)}$$

The two curves represented by eqns. (9.107) and (9.108) specify the edges of the conducting surfaces. They are identical and the relative shape is magnified relative to the other or rotated by an angle δ w.r.t. the other. The magnification or rotation allows the arm of conductor P to have a finite width as shown in Fig. 9.57.



(a) Spiral plate (b) Spiral slot antenna

Fig. 9.57. Spiral plate and slot antenna.

In a similar way, the metallic arm of a second conductor, designated as Q, can be defined as follows

$$r_4 = r_4' e^{a\varphi} = r_2' e^{a(\varphi - \pi)}$$

where

$$r_4' = r_2' e^{-a\pi} \quad \text{... (9.111)}$$

and

$$r_5 = r_5' e^{a\varphi} = r_4' e^{-a\delta} \cdot e^{a\varphi} = r_2' e^{-a\pi} \cdot e^{-a\delta} \cdot e^{a\varphi} = r_2' e^{-a(\pi + \delta)} \cdot e^{a\varphi} \quad \text{... (9.112)}$$

$$r_5 = r_2' e^{a(\varphi - \pi - \delta)}$$

where

$$r_5' = r_4' e^{-a\delta} = r_2' e^{-a\pi} \cdot e^{-a\delta} \quad \text{... (9.113)}$$

$$r_5' = r_2' e^{-a(\pi + \delta)} \quad \text{by eqn. 9.112} \quad \text{... (9.114)}$$

The system composed of the two conducting arms P and Q constitutes a balanced system as shown in Fig. 9.57 (a). Its finite size of structure is specified by the fixed spiralling length L along the centre line of the arm. The entire structure can be completely specified by the rotation angle δ and the arm length L, the rate of spiral $\frac{1}{a}$, and the terminal size r_2'. However, most of the characteristics can be described only by L, r_2' and $K = e^{-a\delta}$. The arm is tapered at its end to provide a better matching termination [shown by dashes in Fig. 9.57 (a)]. The length L of the spiral is given by

5 6 7 8 9 10 11

$$\boxed{L = (r_1 - r_0)\,\sqrt{\frac{a^2+1}{a^2}}} \qquad \frac{\sqrt{a^2+1}}{a^2} \qquad ...(9.115)$$

where r_1 = radius of outer spiral

r_0 = radius of inner spiral

Fig. 9.57 (a) shows an antenna consists of two metallic arm suspended in free space and Fig. 9.57 (b) shows a spiralling slot on a large conducting plane. It can be easily fed by a balanced coaxial line.

The planar equiangular spiral antenna is bi-directional radiating a broad-lobed beam on each side of the plane. The field is circularly polarized if spiral expansion rate is not too rapid. The input impedance depends on a and δ and the terminal separation. Typical values are about 50 to 100 ohms or slightly less than theoretical $\eta_0/2$ = 188 ohms. *

α

9.15.5. *Frequency independent conical — spiral antenna.* The shape of a non-planar spiral can be described by defining the derivative of $f(\theta)$ as

$$\boxed{\frac{df}{d\theta} = f'(\theta) = A\,\delta(\beta - \theta)} \qquad ...(9.116)$$

where β is any angle between the range $0 \le \beta \le \pi$. For given value of β, eqn. 9.116 in conjunction with eqn. 9.103 describes a spiral wrapped on a conical surface. The edges of the conical spiral surface are defined by

$$r_2 = r_2'\, e^{(a \sin\theta_0)\varphi}$$

$$r_2 = r_2'\, e^{b\varphi} \qquad ...(9.117)$$

where $b = a \sin\theta_0$ ...(9.118)

and $r_3 = r_3'\, e^{(a\sin\theta_0)\varphi} = r_2'\, e^{-(a\sin\theta_0)\delta} \cdot e^{(a\sin\theta_0)\varphi}$

$$\boxed{r_3 = r_2'\, e^{a\sin\theta_0(\varphi - \delta)}} \qquad ...(9.119)$$

where $\boxed{r_3' = r_2'\, e^{-(a\sin\theta_0)\delta}}$ ...(9.120)

and θ_0 = half of the total included cone angle.

Larger the values of θ_0 in the range $0 \le \theta \le \pi/2$ lesser the tightly wound spirals.

These eqns corresponds to eqns. (9.107), (9.108), (9.109) for the planar surfaces. The second arm of a balanced system is obtained by defining each of the eqn (9.118), (9.119), (9.120) with shift of 180° or π radian as was done in planar surfaces. The conducting conical spiral is constructed easily by forming the conical arms on the dielectric cone, using printed circuit, which also act as support. *The feed cable is bound to the metal arms which are wrapped around the cone (Fig. 9.58). Symmetry is preserved by using as a dummy cable as is done in planar surface.* The conical equi-angular spiral antenna is fed at the apex by a means of a balanced transmission line carried up inside and along the axis of the cone. Alternatively by coaxial cable carried along and soldered in contact with one of the arms.

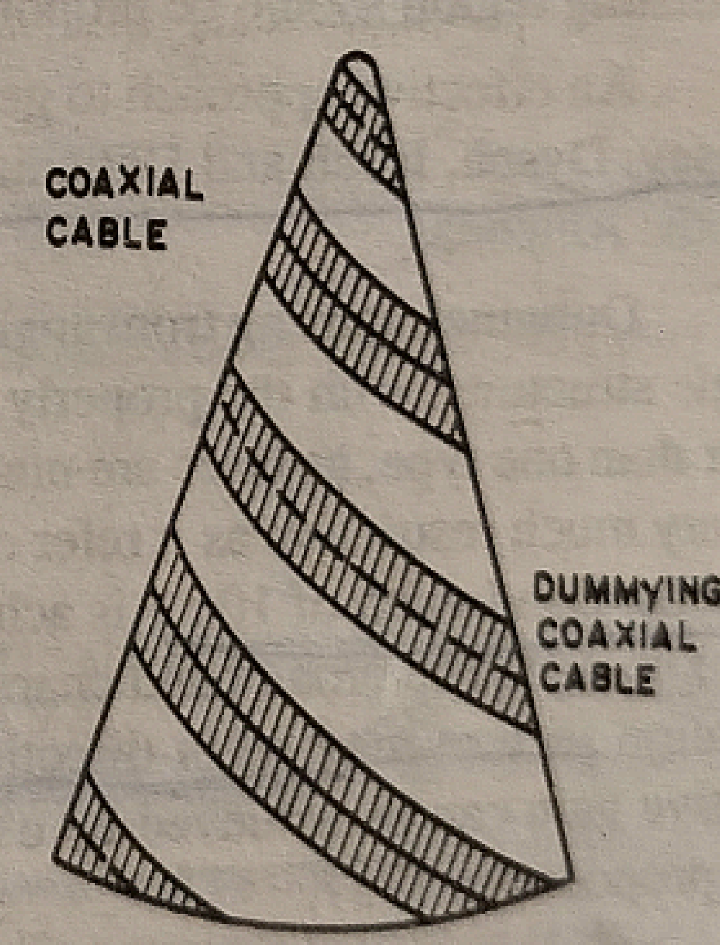


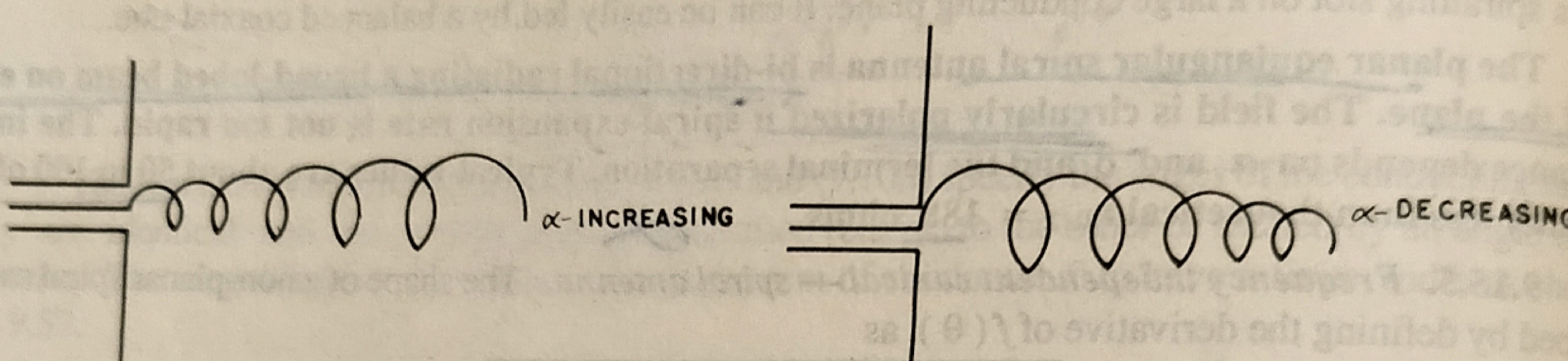
Fig. 9.58. Two arms balanced conical-spiral antenna.

The difference between the planar and conical spiral is that conical spirals provide a *unidirectional radiation single lobe toward the apex of the cone with maximum along the axis. Circular polarization is obtained and relative constant impedances are preserved over bandwidth conical spiral antenna can be used in conjunction with ground plane.*

The input impedance is between 100 to 150 ohms for a pitch angle α = 17° and full angles of 20° to 60°. The smaller cone angles (30° or less) have higher front to back ratios of radiation.

The bandwidth depends on the ratio of the base diameter (nearly $\lambda/2$ at the lowest frequency) to the truncated apex diameter (nearly $\lambda/4$ at the highest frequency). This ratio may be chosen arbitrarily large. Recently bandwidths of 5 to 1 or more have been obtained.

A tapered helix is an example of conical-spiral antenna as shown in Fig. 9.59.



(a) (α-increasing) (b) (α-decreasing)

Fig. 9.59. Circularly polarized Tapered helical or conical spiral antennas.

If the centre of a planar spiral is "pulled out" so that the spiral now lies on a conical surface, the radiation pattern is progressively concentrated more and more in the direction in which the cone is pointing. This changes a bi-directional beam of some 50° to 60° for the planar case, to a unidirectional beam of some 70° to 90° width for a narrow angled cone. For higher front to back ratio better than 15 *db*, the semi-apex angle is not kept more than 15°.