Conclusion

An attempt has been made to describe the general aspects of slot antennas. Such antennas are a "must" in high-speed aeronautics and in radio-controlled missiles.

It has been shown that many of the tasks performed by external antennas can be performed by this flush-type radiator. Subjected to careful scientific investigation, as is possible in peacetime, their usefulness should eventually be greatly extended.

Acknowledgment

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Fundamental Limitations of Small Antennas*

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Summary—A capacitor or inductor operating as a small antenna is theoretically capable of intercepting a certain amount of power, independent of its size, on the assumption of tuning without circuit loss. The practical efficiency relative to this ideal is limited by the "radiation power factor" of the antenna as compared with the power factor and bandwidth of the antenna tuning. The radiation power factor of either kind of antenna is somewhat greater than

$$\frac{1}{6\pi}\frac{Ab}{l^3}$$

in which Ab is the cylindrical volume occupied by the antenna, and l is the radianlength (defined as $1/2\pi$ wavelength) at the operating frequency. The efficiency is further limited by the closeness of coupling of the antenna with its tuner. Other simple formulas are given for the more fundamental properties of small antennas and their behavior in a simple circuit. Examples for 1-Mc. operation in typical circuits indicate a loss of about 35 db for the I.R.E. standard capacitive antenna, 43 db for a large loop occupying a volume of 1 meter square by 0.5 meter axial length, and 64 db for a loop of 1/5 these dimensions.

I. Introduction

An antenna whose dimensions are much less than the wavelength is subject to limitations which can be expressed by simple formulas. These limitations are fundamentally about the same for a capacitor used as an electric dipole and an inductor (loop) used as a magnetic dipole, if they occupy equal volumes. Either type may have some advantages resulting from variations within this rule or from relative facility in coupling with the associated circuits. This paper is directed to a few of the simplest formulas, and to their significance and application rather than their derivation. The small antenna to be considered is one whose maximum dimension is less than the "radianlength." The radianlength is $1/2\pi$ wavelength; it proves to be a logical unit for this purpose and a convenient one for simplifying the concepts and formulas. The approximations involved within this size depend only on the closeness between an angle and its sine up to $\frac{1}{2}$ radian (4 per cent error). An antenna within this limit of size can be made to behave essentially as lumped capacitance or inductance, so this property is assumed.

It has occasionally been pointed out that a small antenna free of dissipation could take from a radio wave and deliver to a load an amount of power independent of the size of the antenna. This would be true at one frequency if the antenna can be resonated at that frequency without adding dissipation. It results from the fact that a smaller antenna delivers its lesser voltage from a lesser resistance such that the available power remains the same.

The power available from such an antenna is the wave power which would pass through the "effective area" of the antenna. Its effective area is 3/2 the area of a circle whose radius is one radianlength, denoted a "radian circle." The factor 3/2 is the power ratio of the directive gain of a small antenna relative to a theoretical antenna conceived to radiate equally in all directions over the sphere, denoted an "isotropic" antenna. This factor results from the fact that a small dipole (electric or magnetic) radiates in a doughnut pattern which effectively fills only 2/3 of the entire solid angle of a sphere.

Formulas for the efficiency of transmission through space may be stated in terms of the power actually radiated from the transmitting antenna and the power theoretically available from the receiving antenna to a load. In each case, the unavoidable dissipation in the coupling circuit (from generator to antenna or from antenna to load) limits the output to only a fraction of the power input. This fraction is the efficiency of the coupling circuit.

While the radiation pattern and hence the directive gain of a small antenna remain the same for a smaller size, the radiation resistance decreases relative to the other resistance in the coupling circuit. The resulting reduction in coupling efficiency is one of the principal limitations of the smaller antenna.

Another aspect of the same limitation relates to the frequency bandwidth of operation with fixed values of

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the circuit elements. A smaller antenna with the same reactance and radiation resistance must be more sharply tuned to deliver its available power. Therefore, the reluction of size imposes a fundamental limitation on the bandwidth. If the bandwidth so limited is insufficient, further damping must be added at the expense of coupling efficiency.

The limitations verify the experience that larger antennas are generally more efficient, especially for wide-band operation.

By expressing the formulas in fundamental forms, the inherent similarity of the electric and magnetic radiators becomes apparent, as well as the minor differences resulting from the use of available materials and structures.

II. Symbols

a = radius of circular cylindrical volume (meters)
A = area of base of cylindrical volume (meters^2)
b = height of cylindrical volume (meters)
n = number of turns of coil
k_a = shape factor of capacitor = effective area/actual area (A)
k_b = shape factor of inductor = effective length/actual length (b)
C = capacitance of antenna (farads)
L = inductance of antenna (henries)
ω = radian frequency (radians/second)
λ = wavelength (meters)
$l = \lambda/2\pi$ = radianlength (meters)
ϵ = electric permittivity in free space (farads/meter)
μ = magnetic permeability in free space (henries/meter)
k_e = relative permittivity of core in capacitor
k_m = relative permeability of core in inductor
$R = 120\pi = 377$ = wave resistance in free space (ohms)
$G = 1/R$ = wave conductance in free space (mhos)
R_e, R_m = radiation resistance in series with antenna (ohms)
G_e, G_m = radiation conductance in parallel with antenna (mhos)
R_t, G_t = series resistance or shunt conductance in tuner (ohms, mhos)
C_t, L_t = shunt capacitance or series inductance in tuner (farads, henries)
p_e = radiation power factor of capacitor antenna (electric dipole)
p_m = radiation power factor of inductor antenna (magnetic dipole)
k_c = coefficient of coupling between antenna and total capacitance
k_i = coefficient of coupling between antenna and total inductance
k_c^2 = efficiency of coupling of antenna to total capacitance = electric energy in antenna/total electric energy in tuned circuit
k_i^2 = efficiency of coupling of antenna to total inductance = magnetic energy in antenna/total magnetic energy in tuned circuit
e = radiation efficiency of antenna circuit.

III. Formulas

(C) (L)

Capacitance and inductance:

$$C = \epsilon \frac{k_a A}{b}; \qquad L = \mu n^2 \frac{A}{k_b b}. \tag{1}$$

Susceptance and reactance:

$$\omega C = G \frac{k_a A}{bl}; \qquad \omega L = R n^2 \frac{A}{k_b b l}. \tag{2}$$

Radiation shunt conductance and series resistance:

$$G_e = \frac{G}{6\pi}\left(\frac{k_a A}{l^2}\right)^2; \qquad R_m = \frac{R}{6\pi}\left(\frac{nA}{l^2}\right)^2 = 20\left(\frac{nA}{l^2}\right)^2 \tag{3}$$

$$R_e = \frac{R}{6\pi}\left(\frac{b}{l}\right)^2 = 20\left(\frac{b}{l}\right)^2; \quad G_m = \frac{G}{6\pi n^2}\left(\frac{k_b b}{l}\right)^2. \tag{4}$$

Radiation power factor:

$$p_e = \frac{G_e}{\omega C} = \frac{1}{6\pi}\frac{k_a A b}{l^3}; \qquad p_m = \frac{R_m}{\omega L} = \frac{1}{6\pi}\frac{k_b A b}{l^3}. \tag{5}$$

Coupling efficiency, connected as in Fig. 2:

$$k_c^2 = \frac{C}{C + C_t}; \qquad k_i^2 = \frac{L}{L + L_t}. \tag{6}$$

Circuit efficiency, connected as in Fig. 2:

$$e = \frac{G_e}{G_e + G_t}; \qquad e = \frac{R_m}{R_m + R_t}. \tag{7}$$

Circuit efficiency, in general:

$$e = \frac{k_c^2 p_e}{k_c^2 p_e + p_t}; \qquad e = \frac{k_i^2 p_m}{k_i^2 p_m + p_t}. \tag{8}$$

IV. The Antenna

Fig. 1 shows two antennas occupying volumes alike in shape and size, one being a capacitor (C) and the

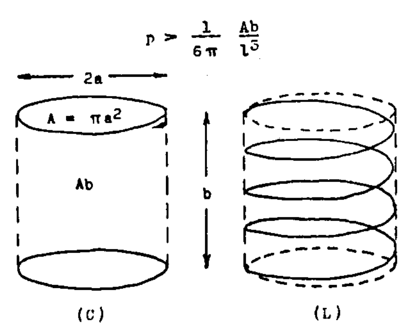

Fig. 1—Capacitor (C) and inductor (L) occupying equal cylindrical volumes.

other an inductor (L). Their maximum dimensions are less than the radianlength of operation. Their shapes are cylindrical because that is the only shape that can alternatively be occupied by either a capacitor or an inductor. The volume may be bounded by a circular cylinder, as shown, or by other cylinders such as square or rectangular.

In both cases, the antenna is assumed to operate as a lumped circuit element of the kind indicated (C or L), neglecting distributed properties. The inductor (loop antenna) is assumed to act as a current sheet pervious to alternating magnetic flux, as is customary in the theory of solenoidal coils: this assumption is justified if the coil is wound of several turns of wire or ribbon having a width of about $\frac{1}{2}$ the pitch of winding.

The symbols and principal formulas are tabulated above for convenience. All formulas have the same form for the two kinds of antennas, except for the number of turns n and the correction factors k_a and k_b. These factors are defined to have such values that (1) gives the correct values of C and L.

For the capacitor, the correction factor k_a multiplies the area A to obtain the effective area, as augmented by the electric field outside the cylindrical volume. This factor is greater than unity and (for circular disks, $A=\pi a^2$) greater than

$$\frac{4}{\pi}\frac{b}{a} = 1.27\frac{b}{a}, \tag{9}$$

based on two disks far apart. The value of k_a is asymptotic to unity for $b \ll a$, and is asymptotic to (9) for $b \gg a$.

For the inductor, the correction factor k_b multiplies the axial length b to obtain the effective length of the magnetic path as augmented by the external return path. This factor also is greater than unity. If $b>a$ for a circular coil ($A=\pi a^2$), this factor is closely approximated by the asymptotic value:

$$k_b = 1 + \frac{8}{3\pi}\frac{a}{b}; \quad \text{or better,} \quad k_b = 1 + 0.9\frac{a}{b}\cdot \tag{10}$$

The effective volume becomes

$$k_b Ab = Ab + 0.9aA = Ab + 2.8a^3. \tag{11}$$

If $b<a$, the factor is somewhat less than this value.

The electric-dipole radiation from the capacitor is represented by shunt conductance G_e or series resistance R_e. The magnetic-dipole radiation from the inductor is represented by series resistance R_m or shunt conductance G_m. In both kinds of antenna the resistance formula is free of the correction factor, because the radiation is caused by the current which is confined to certain definite dimensions of the structure. Therefore, the radiation resistance is the concept ordinarily used. Its value is given not only in the general form but also in the simplified form valid in free space.

The fundamental limitation on the bandwidth and the practical efficiency of a small antenna is the radiation power factor, p_e or p_m, given by (5). It is always much less than unity because of the small size. It has the same value, whether computed from radiation resistance or conductance. It has the same form for both kinds of antennas. Its value, except for the correction factor, is the same for both kinds, and depends only on the ratio of the antenna volume Ab to the radian cube l_t.

In (5) the coefficient $1/6\pi$ is the product of the two factors $1/4\pi$ and $2/3$. The former is the reciprocal of the solid angle of a sphere, which appears in rationalized formulas involving spherical waves. The latter is the fraction of the sphere which is filled with the doughnut pattern of radiation characteristic of a small dipole.

As a special case of the radiation power factor, consider an antenna occupying a cubic space Ab equal to a radian cube l^3. The resulting power factor is $1/6\pi = 0.053$, multiplied by the correction factor. In this case, approximately, $k_a=2.7$ and $k_b=1.5$, so the power factors are $p_e=0.14$ and $p_m=0.08$. Therefore, this size of antenna has sufficient radiation damping to operate over a bandwidth of the order of 1/10 the mean frequency, even if there is no other damping.

A cubic antenna of this size (and one turn on the inductor) has a reactance comparable with the wave resistance of the medium ($R=1/G=120\pi=377$ ohms in free space). The reactance ($1/\omega C$ or ωL) of each kind is reduced by the correction factor, so it has a value of 140 ohms for the capacitor, or 250 ohms for the inductor. Reducing the size or the frequency increases the reactance of the capacitor and reduces that of the inductor. The latter has greater flexibility in that its reactance can be increased with the number of turns.

In the cubic shape, the correction factor is slightly greater for the capacitor than for the inductor. This advantage is real, though it is small and may be overbalanced, in some cases, by circuit disadvantages.

If the axis of the cylinder is vertical, either antenna radiates in a pattern like a horizontal doughnut. Since the polarization is expressed with reference to the electric field, the capacitor radiates with vertical polarization and the inductor with horizontal. The required polarization is likely to be the determining factor in choosing which kind to use, if the horizontal doughnut is the desired pattern of radiation.

A plane reflector doubles the radiation power factor if it is located lose enough to either kind of antenna and in such relation as to re-enforce the radiation. The plane reflector acts by virtue of its great conductivity or relative permittivity. A surface of water or ground may approximate a plane reflector. The size of the antenna and its proximity to the reflector must be such that the antenna and its image fall within a maximum dimension less than the radianlength, if the radiation power factor of (5) is to be doubled. Also, the reflector must have a radius greater than 1/4 wavelength. To re-enforce the radiation, the plane must be perpendicular to the axis of the capacitor or parallel to the axis of the inductor, so the polarization is perpendicular to the plane.

The cylindrical volume may be filled with a dielectric core in the capacitor or a magnetic core in the inductor. In either case, the radiation shunt conductance (not the series resistance) remains the same, because it is determined by the energy in the field outside of the antenna, regardless of that inside. A dielectric core of relative permittivity k_e increases the capacitance to

$$C = \epsilon \frac{A}{b}(k_a + k_e - 1) \tag{12}$$

approximately if $b<2a$. This reduces the radiation power factor in the ratio

$$\frac{k_a}{k_a + k_e - 1} = \frac{1}{1 + \dfrac{k_e - 1}{k_a}}. \tag{13}$$

A magnetic core of relative permeability k_m increases the inductance to

$$L = \mu n^2 \frac{A}{b(k_b + 1/k_m - 1)} \tag{14}$$

approximately if $b>2a$. This increases the radiation power factor in the ratio

$$\frac{1}{1 - \dfrac{k_m - 1}{k_m k_b}} = \frac{1 + 0.9\dfrac{a}{b}}{\dfrac{1}{k_m} + 0.9\dfrac{a}{b}}. \tag{15}$$

The efficiency may be further increased by reduction in the effective coil resistance.

The structure of the antenna is a subject by itself, outside the scope of this monograph.

The same principles may be applied to the design of a reactor in which radiation is undesired and low power factor ("high Q") is desired. If the reactor is unshielded, the optimum size is a compromise between larger size to reduce internal series resistance and smaller size to reduce internal shunt conductance and radiation. The optimum size for a single-layer coil with negligible dielectric power factor is that for which the radiation power factor is a minor fraction of the total, say between 1/6 and 1/2, depending on the nature of the factors which determine the internal resistance. In ordinary cases, the volume of the coil should not exceed about 1/100 of a radian cube, which means the diameter and length, if equal, should not exceed about 1/5 radian-length, or 1/30 wavelength. If this size is too small, a larger coil with shielding may be required.

V. The Circuits

Efficient operation of a small antenna requires tuning to the operating frequency with a circuit which offers little additional dissipation. How much the circuit may detract from the efficiency depends on the nature of the generator or load coupled therewith, and on other requirements such as bandwidth. The simplest case will be described as an example.

Fig. 2 shows a generator or load coupled with an antenna of either kind (C or L) through its tuner. In the

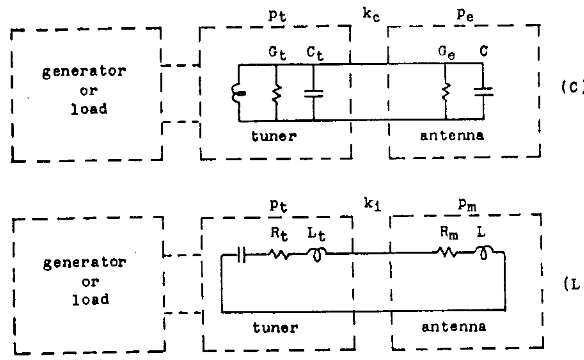

Fig. 2—Tuned coupling of antenna with generator or load.

case of a generator, it is assumed that it is so coupled with the tuner as to deliver all of its available power to the tuner and antenna. In the case of a load, it is assumed that it is so coupled with the tuner as to receive the maximum power therefrom, which is called the "available power."

In general, the efficiency of the coupling circuit is increased by increasing the coefficient of coupling between the tuner and the antenna, and by decreasing the power factor of the tuner.

The coefficient of coupling (k_c or k_i) between the tuner and the antenna is defined in the usual way. Its square is called the "coupling efficiency" because it denotes the fraction of the total electric or magnetic energy of the tuned circuit which is in the antenna. It is expressed in (6) for the simple connection of Fig. 2, but has more general significance.

The power factor p_t of the tuner is taken to include all dissipation in the tuner and antenna, except the desired radiation. In Fig. 2, this is lumped in the effective shunt conductance G_t or the effective series resistance R_t. It is connected directly in parallel or in series with the radiation effective conductance G_e or resistance R_m. In this connection the circuit efficiency is merely the ratio of the radiation power to the total power in the circuit, as expressed in (7).

The more general expression of circuit efficiency is given by (8), in terms of power factor and coupling efficiency. This gives an indication of the relative importance of all factors.

After the coupling circuit has been designed for the maximum efficiency at the frequency of resonance, consistent with available space, materials, and precision, the total power factor of the circuit will exceed $k_c^2 p_e$ or $k_i^2 p_m$ by the amount of the tuner power factor p_t and the added power factor contributed by the generator or load. If the antenna comprises all the reactance of one kind in the circuit, and the tuner losses are small, the total power factor of the circuit may be that of the antenna plus an equal value coupled from the generator or load. Therefore, a very efficient design may have a loaded power factor $2p_e$ or $2p_m$, and a corresponding bandwidth of the tuned circuit.

If the bandwidth desired in the coupling circuit is either less or greater than that obtained by designing for maximum efficiency at the frequency of resonance, the redesign for different bandwidth will be at the expense of efficiency. Lesser bandwidth may be obtained by decreasing the coupling with generator or load, decreasing the coupling between tuner and antenna, multiple tuning, or decreasing the antenna size. Greater bandwidth may be obtained by increasing the coupling with generator or load, increasing the power factor of the tuner, or developing the tuner into a wide-band circuit.

Some types of generator or load do not double the power factor of the tuned circuit when coupled for normal operation. An efficiency generator, for example, operates best into an impedance much different from its internal impedance. A current generator of high resistance, such as a high-μ screen-grid tube, contributes little damping to a tuned output circuit. On the other hand, a voltage generator of low resistance, such as a low-μ triode tube or cathode-output circuit, more than doubles the damping in a tuned output circuit. Likewise, there are load circuits which are essentially voltage-operated, such as a voltmeter or the grid circuit of an amplifier; or current-operated, such as an ammeter. Either type of load may not be designed to utilize the available power, in which case it may add little to the damping. In view of the various effects of the associated circuits, the radiation power factor of the antenna is not the ultimate limitation on the bandwidth of efficient operation, but does indicate the order of magnitude and the trends with changes of antenna design.

VI. Examples

First example: A loop antenna is intended for operation with horizontal axis in a radio receiver cabinet in a small frame building. Its size is 1 meter square by 0.5 meter axial length.

Wavelength:	$\lambda=$	300	m. (at 1 Mc.)
Radianlength:	$l=$	48	m.
Radian cube:	$l^3=$	110,000	m.^{3}
Antenna volume:	$Ab=$	0.5	m.^{3}
Shape factor:	$k_b=$	2	

The radiation power factor is computed by doubling (5) to include approximately the effect of the ground plane.

Radiation power factor: $p_m=0.96\times10^{-6}$.

The loop is assumed to be one-half the entire inductance of the tuned circuit (6).

Coupling efficiency: $k_i^2=0.5$.

The power factor of the entire tuned circuit is assumed to be 0.01 and the efficiency is computed from (8).

Efficiency: $e=0.48\times10^{-6}/0.01=0.048\times10^{-3}$.

This represents a loss of 43 db. It is noted that the essential performance is obtained without reference to incidental factors, such as the number of turns, which are supplied by ordinary design procedure.

A capacitive antenna of comparable volume would give comparable performance, with some practical advantages and disadvantages. Its disuse indicates that the disadvantages usually predominate.

A loop antenna as small as 1/5 the dimensions of this example, namely, $0.2\times0.2\times0.1$ meter, is used in small receivers. The efficiency is approximately 0.4×10^{-6}, representing a loss of 64 db at 1 Mc.

Second example: A capacitive antenna over ground is connected with a radio receiver. The antenna is a wire so its area is undefined. Including lead-in, its effective height is 4 meters and its capacitance is 200 micro-microfarads, the I.R.E. standard. Therefore, its effective area is determined by (1).

Antenna capacitance:	$C=$	200 $\mu\mu$fd.
Effective height:	$b=$	4 m.
Effective area:	$k_aA=bC/\epsilon=$	90 m.^{2}
Effective volume:	$k_aAb=$	360 m.^{3}
Wavelength:	$\lambda=$	300 m. (at 1 Mc.)
Radianlength:	$l=$	48 m.
Radian cube:	$l^3=$	110,000 m.^{3}

The radiation power factor over the ground plane is computed by doubling (5).

Radiation power factor: $p_e=0.35\times10^{-3}$.

The coupling efficiency is assumed to be reduced to about 0.01 so large variations of antenna will not cause appreciable detuning of the circuit.

Coupling efficiency: $k_e=0.01$.

The power factor of the entire tuned circuit is assumed to be 0.01 and the efficiency is computed from (8).

Efficiency: $e=0.35\times10^{-3}$.

This is a loss of 35 db, chargeable 15 db to circuit dissipation and 20 db to decoupling for reducing the reaction of antenna changes on the tuning. Part of the latter (20 db) can be recovered by greater coupling and providing for retuning on each antenna. Otherwise, it is noted that this antenna is only 8 db better than the loop antenna of the first example.

Third example: A loop antenna is intended for operation with vertical axis in a television receiver cabinet. Its size is 0.5 meter cube. It is tuned to the desired frequency channel.

Wavelength:	$\lambda=5$	m. (at 60 Mc.)
Radianlength:	$l=0.8$	m.
Radian cube:	$l^3=0.51$	m.^{3}
Antenna volume:	$Ab=0.12$	m.^{3}
Shape factor:	$k_b=1.5$	
Radiation power factor:	$p_m=0.019$.	

Since the required bandwidth is about 0.1 of the center frequency, or about $5p_m$, there is a loss of only 4 to 7 db, depending on the nature of the circuits connected with the antenna for increasing the bandwidth.

Fourth example: A loop antenna is intended for operation with horizontal axis in a portable f.m. receiver. Its size is 0.2 meter cube. It is tuned to the desired frequency. All losses except radiation and load are assumed to yield a tuner power factor of 0.01.

Wavelength:	$\lambda = 3$	m. (at 100 Mc.)
Radianlength:	$l = 0.48$	m.
Radian cube:	$l^3 = 0.11$	m.^{3}
Antenna volume:	$A_b = 0.008$	m.^{3}
Shape factor:	$k_b = 1.5$	
Radiation power factor:	$p_m = 0.0058$	
Tuner power factor:	$p_t = 0.01$	
Efficiency:	$e = 0.37.$	

This is a circuit loss of 4 db. The bandwidth is 2 or 3 Mc., more than enough for a single channel 0.2 Mc. wide. However, if the same antenna were required to cover the entire band of 88 to 108 Mc. without retuning, a width of 0.2 times the mean frequency, the loss would be 12 to 15 db caused by the wide-band circuit.

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A Helical Antenna for Circular Polarization*

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Summary—A helical coil radiates a wave of circular polarization in a doughnut pattern if the area and pitch of the turns are properly related to the radianlength of the wave. For a coil whose dimensions are less than the radianlength, circular polarization requires that the area A of each turn and the pitch p be related to the radianlength l as follows:

$$A = pl.$$

The simplest form of helical antenna is a self-resonant coil of several turns. To obtain greater radiation power factor and efficiency, a multifilar winding is preferred, having a fractional turn for each of several helical wires connected in parallel with symmetry around the axis. This type of antenna offers television the advantages of circular polarization in suppressing echoes from reflecting surfaces.

I. Introduction

A HELICAL COIL can be designed to radiate waves of circular polarization by properly proportioning the area and pitch of the turns with relation to the wavelength or radianlength. The screw direction of the helix determines the direction of rotation of the wave polarization. The simplest case of this helical antenna is a small one whose dimensions are less than the radianlength.

A small antenna whose dimensions are less than the radianlength behaves essentially as a dipole with a coaxial doughnut pattern of radiation. If it is an electric dipole or current element, the polarization of the electric vector is in the plane of the dipole. If it is a magnetic dipole or current loop, the polarization of the electric vector is normal to the plane of the dipole (the plane through the axis of the loop).

The helical antenna is a superposition of electric and magnetic dipoles to radiate a wave with circular polarization. Reference (9) of the Bibliography shows that a capacitor and an inductor occupying equal cylindrical volumes have approximately the same power factor of radiation. If these are made of equal reactance and connected together to form a circuit resonant at the operating frequency, it follows that the radiated power is about equally divided between the electric-dipole radiation from the capacitor and the magnetic-dipole radiation from the inductor.

A coaxial superposition of the capacitor and inductor is possible if the structure of each is designed to give the required freedom to both fields; there is no inconsistency in their coexistence in the same space.

Circular polarization requires two relations between the crossed fields in a wave. They must have equal intensity and phase quadrature in time. Then the direction of rotation of the polarization depends on the phase sequence of the crossed components of either field.

The helical antenna inherently obtains the phase quadrature. The equality of intensity of the crossed components is obtained by making the area of each turn equal to the product of the pitch of the turn times the radianlength ($1/2\pi$ wavelength). The rotation is determined by the screw direction of the helix. Ideally, there should be no other radiating or reflecting conductors in the vicinity. Capacitive loading at the ends of the coil is permissible, as well as circuit connections

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