

United States Patent

[11] 3,605,097

[72] Inventor **Endre B. Hadik-Barkoczy**
Belmont, Calif.
 [21] Appl. No. **841,210**
 [22] Filed **July 14, 1969**
 [45] Patented **Sept. 14, 1971**
 [73] Assignee **Textron Inc.**
Belmont, Calif.
 Continuation-in-part of application Ser. No. 725,987, May 2, 1968, now abandoned.

[56]

References Cited

UNITED STATES PATENTS

2,659,004	11/1953	Lindenblad	343/705
3,268,896	8/1966	Spitz	343/708

FOREIGN PATENTS

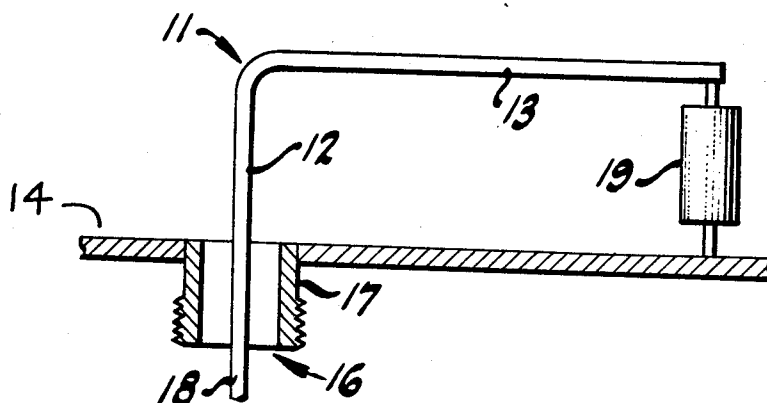
424,698	2/1935	Great Britain	343/739
708,799	5/1954	Great Britain	343/712

Primary Examiner—Eli Lieberman
 Attorney—Gregg & Hendricson

[54] **END-LOADED FILAMENT ANTENNA**
 9 Claims, 9 Drawing Figs.

[52] U.S. Cl. 343/739,
 343/830, 343/845
 [51] Int. Cl. H01q 11/02
 [50] Field of Search 343/705,
 708, 711-713, 739, 741, 825, 829, 830, 845, 846

ABSTRACT: This invention relates to an electrically small antenna having a directional radiation pattern. The invention is physically embodied as a small filament, extending upwardly from a ground plane into connection with the top of a small passive resistor in turn extending downwardly to the ground plane. This filament lies in a single plane and produces linearly polarized radiation in such plane, with maximum radiation in a predetermined direction in such plane and elliptically polarized radiation in other planes but still with maximum radiation in a single direction.



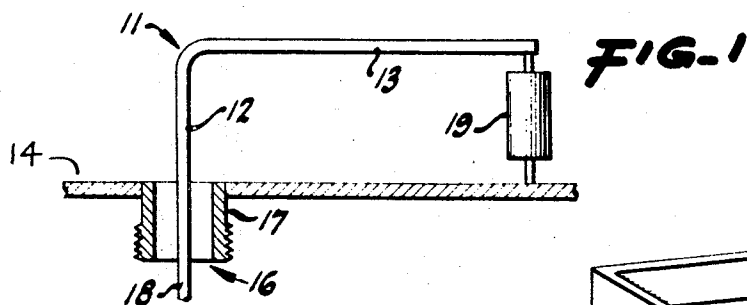


FIG. 1

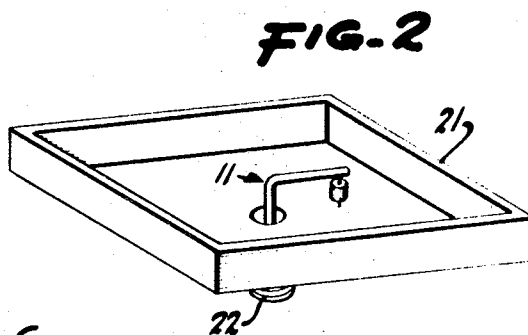


FIG. 2

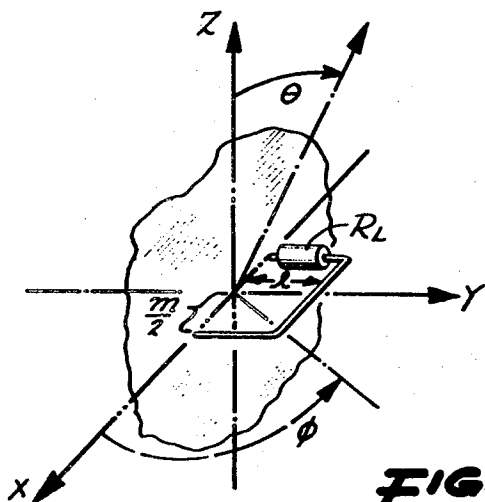


FIG. 3

FIG. 5

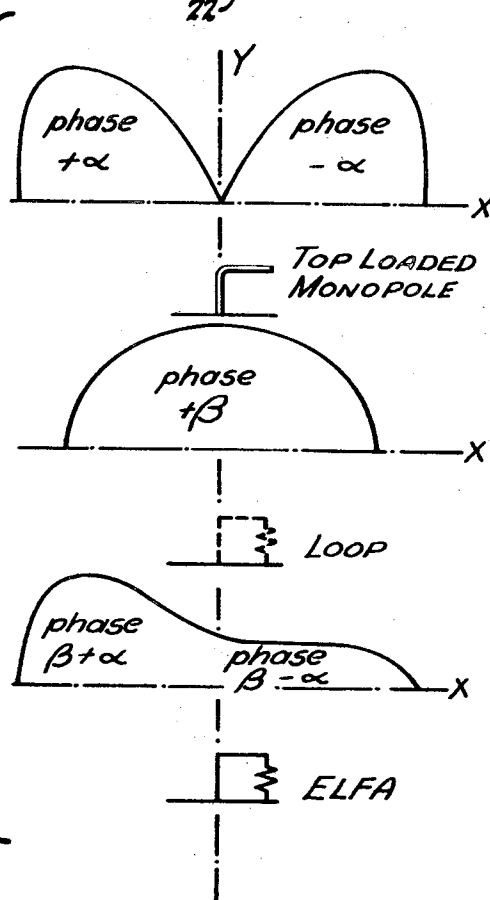
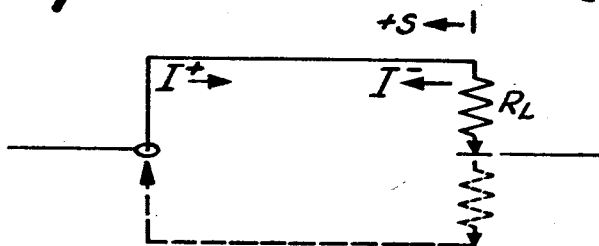


FIG. 4



INVENTOR
ENDRE B. HADIK-BARKOCZY
BY *Hegg & Henderson*
ATTORNEYS

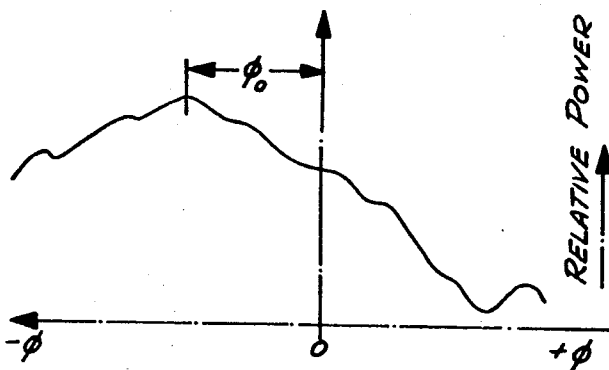


FIG. 6

FIG. 7

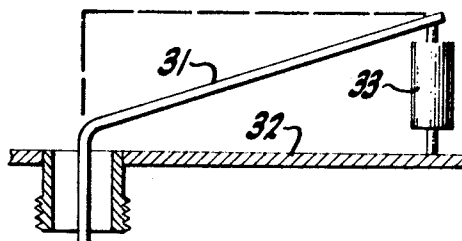
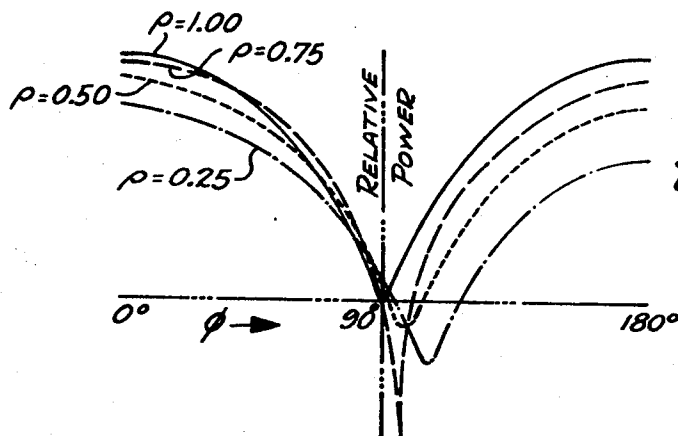


FIG. 8

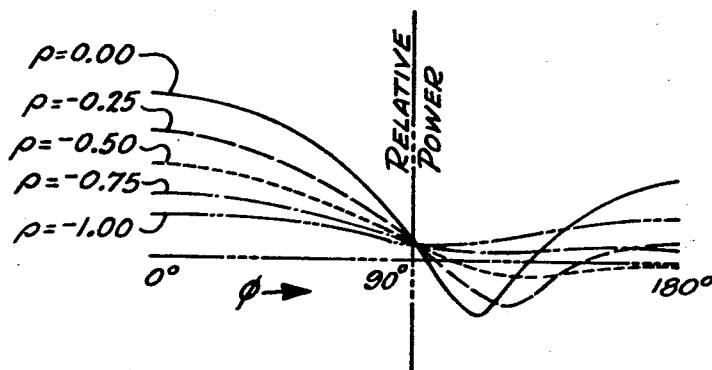


FIG. 9

INVENTOR
 ENDRE B. HADIK-BARKOCZY
 BY *Shegg & Henderson*
 ATTORNEYS

END-LOADED FILAMENT ANTENNA

This is a continuation-in-part of my copending U.S. Pat. application Ser. No. 725,987 filed May 2, 1968, now abandoned for "End-Loaded Filament Antenna."

BACKGROUND OF INVENTION

An almost innumerable number of different antenna structures and arrays have been developed for particular transmitting and receiving purposes. One general type of antenna is that commonly denominated as a directional antenna. In this general field there are known various methods and means of producing directional radiation, as, for example, by the utilization of resonant antenna structures. For many, and in fact for most, antenna applications, it is considered desirable to simplify the structure and to minimize the physical dimensions. Conventional directional antennas do incorporate a substantial complexity and normally have a substantial size. Although antennas of the general type termed "electrically small antennas" are known in the art, it has heretofore been considered that such antennas are not applicable for directional propagation or reception.

Although not directed to the field of directional radiation, there have been developed certain shortened, or miniaturized antenna structures, which superficially resemble the structure of the present invention. Thus, for example, U.S. Pat. No. 2,994,876 to Josephson discloses an ultrashortwave antenna comprising a folded unipole loaded with an impedance to thus establish a displaced feed point. U.S. Pat. No. 3,295,137 to Fenwick et al. teaches the use of ferrite discs disposed about the grounded leg of a short, folded antenna structure for improving radiation efficiency. These above-noted patents are only exemplary of a large number of patents in the field relating to miniaturization of antenna structures, however, they are to be distinguished from the present invention.

An important aspect of the present invention is the limited physical size thereof and in this respect the term "electrically small" is employed herein. Although this term has been previously employed in the art, it appears that the definition thereof is quite variable and thus for the purpose of the present invention it is taken to mean a length of the order of one-tenth free space wavelength at the highest operating frequency of the antenna and no more than two-tenths of such wavelength. This limitation upon the size is obtained herein from a determination of far-field vector potentials and an arbitrary toleration of a 5 percent error in the vector field of the filament segment carrying a quasi-constant current. Thus as herein employed the term "electrically small" is taken to mean a length not in excess of 0.20 of the free space wavelength at the highest operating frequency of the antenna.

It is recognized that electrically small antennas are known in the art having frequency independent radiation patterns, however, such radiation patterns usually vary as a cosine function. The electrically small antenna of the present invention is also frequency independent but produces a radiation pattern having a maximum in a predetermined direction to maintain a beam tilt or direction.

SUMMARY OF INVENTION

The present invention comprises an electrically short filament disposed in extension from and across a ground plane. In describing the invention it is convenient under certain circumstances to consider the ground plane as being horizontal however, with regard to theoretical considerations, certain identified portions of the following description of the invention employs a vertical ground plane. It is to be appreciated that the physical location or orientation of the ground plane from which the antenna of the present invention extends is not germane to the invention itself, however, as noted above, it is convenient for the purposes of explanation to locate the ground plane in the horizontal or vertical direction in order to be able to employ commonly used descriptive terms with relation to the direction of extension of elements, fields and the like.

Considering the ground plane to be horizontal, the present invention is then comprised of a thin filament radiator extending vertically through the ground plane out of electrical contact therewith and across a portion of the ground plane to a terminus. An end-loading resistor is electrically connected between the outer terminus of the filament radiator and the ground plane. A feed point is established where the filament radiator extends through the ground plane and this may, for example, be comprised of a coaxial cable having the sheath thereof electrically connected to the ground plane and the central conductor thereof connected to the end of the filament radiator.

The filament radiator and resistor of the present invention are disposed in a single plane and for the purposes of the following derivations and description it is convenient to consider this filament radiator as having an L-shaped configuration with one leg extending perpendicularly through the ground plane out of contact therewith and the other extending parallel to the ground plane to the above-noted end-loading resistor. The present invention provides for establishing a directional radiation pattern in the plane of the filament radiator thereof and having a maximum radiation in such a plane in a direction away from the end-loading resistor.

The invention may be readily understood as to the beam radiation pattern thereof by considering the antenna both as a top-loaded monopole radiator and as a loop radiator. The radiation pattern for a top-loaded monopole extending from the ground plane is a lobe above the ground plane in each of the two quadrants in the principal plane of the monopole. It is, however, to be appreciated that the phase of radiated energy is opposite in the two above-noted quadrants. Considering the invention as a loop antenna it will be appreciated that there is produced a single relatively hemispherical lobe of radiation above the ground plane centered about an axis of the upright portion of the lobe extending from the ground plane and having the same phase in all portions of the lobe. Addition of these two monopole and loop radiation patterns causes a phase addition in one quadrant of the principle plane and a phase subtraction in the other quadrant thereof so as to achieve a directivity of radiation. This directivity of radiation from the antenna of the present invention is a function of the surge impedance of the antenna, considered as a transmission line, and the end-loading resistance.

DESCRIPTION OF FIGURES

The present invention is illustrated as to particular preferred embodiments thereof in the accompanying drawings wherein:

FIG. 1 is a schematic illustration of a preferred embodiment of the present invention;

FIG. 2 is a perspective view of a preferred embodiment of the present invention;

FIG. 3 is a schematic illustration of the invention with reference axes and indicated angles and dimensions as employed in the derivation of antenna formula in the following description of the invention;

FIG. 4 is a wholly schematic illustration of the invention comprised as a two-wire transmission line including a reflection circuit in the ground plane of the antenna;

FIG. 5 is a series of schematic illustration showing radiation patterns of a monopole antenna, a loop antenna and the combination thereof such as occurs in the present invention;

FIG. 6 is a plot of radiation pattern in the E-plane of an antenna formed in accordance with the present invention;

FIG. 7 is a schematic representation of an alternative embodiment of the present invention; and

FIGS. 8 and 9 are plots of relationships between radiation and reflection coefficient of the antenna.

DESCRIPTION OF PREFERRED EMBODIMENTS

Referring first to FIG. 1 of the drawing, it will be seen that a preferred embodiment of the present invention comprises a

filamentary radiator 11 having first and second sections 12 and 13 extending perpendicularly to each other. These two filament sections 12 and 13 are contiguous, and the total length of the filament is made equal to or less than two-tenths of the free-space wavelength of the highest frequency of energy to be radiated from or received by the antenna. This radiator 11 is mounted in extension above an electrically conducting ground plane, illustrated as a grounded metal plate 14, and may be fed from a coaxial cable 16. This coaxial cable has the outer conductor 17 thereof electrically connected to the ground plane 14, and the inner conductor 18 thereof connected to the free end of the antenna-filament section 12, as indicated.

A further portion of the present invention is a passive end-loading impedance 19, such as a carbon resistor, electrically connecting the free end of the antenna-filament section 13 to the ground plane. It will thus be seen that there is provided a complete electrical circuit from the center conductor 18 of the coaxial cable through the radiator 11 and the resistor 19 to the ground plane 14, and thence back to the outer conductor 17 of the cable 14. As illustrated in FIG. 1, the plate 14 may be considered as lying in a horizontal plane with the filament section 12 extending vertically therefrom, and the filament section 13 being disposed horizontally in parallelism with the plate 14 above same a distance equal to the length of the filament section 12. These conventions are only taken herein as convenient for purposes of description, for, of course, the ground plane may be oriented in any desired manner. It is considered herein that the antenna shall be energized, as through the coaxial cable illustrated, to thereby cause a current to flow in the filament, or radiator 11 for the radiation of electromagnetic waves therefrom. It is furthermore considered that the passive impedance 19 is a pure resistor that ideally does not radiate electromagnetic waves. This latter assumption is substantially correct, and it is noted that the resistor is also chosen to provide an impedance match.

A practical mounting of the present invention is illustrated in FIG. 2, wherein the filamentary radiator 11 is shown to be disposed in a shallow metal tray 21 with the filament section 12 extending perpendicularly upward from the bottom surface thereof. A coaxial-cable connector 22 is mounted on the underside of the tray 21, with the filamentary radiator electrically connected to the center conductor thereof and the tray connected to the outer conductor thereof. The end-loading resistor 19 is illustrated to be physically connected between the free end of the radiator section 13 and the upper surface of the tray floor. It is particularly emphasized at this point that the tray 21 serves only as a ground plane, like the plate 14 of FIG. 1, and does not otherwise contribute to the directional properties of the present invention. Furthermore, the tray may be filled with absorbing material to prevent the tray from causing unwanted radiation.

Considering the radiation pattern about the antenna of the present invention, reference is first made to FIGS. 3, 4 and 5 in conjunction with the following considerations.

First, insofar as general considerations are concerned, it is noted that the present invention, particularly as described above, may be considered both as a top loaded monopole radiator and as a loop radiator. This general approach to the problem is of assistance in attaining a basic understanding of the manner in which directivity of the radiation pattern is attained hereby. Referring to FIG. 5 it will be seen that a top-loaded monopole antenna will produce a radiation pattern having two lobes having opposite phase angles, identified in the figure as $+\alpha$ and $-\alpha$ and lying in the XY plane of the figure. Considering the invention as a loop antenna there will, in accordance with conventional theory, be produced a single lobe radiation pattern having a positive phase angle β , as shown at FIG. 5b and also lying in the XY plane. A combination of these two antennas, i.e., top loaded monopole and loop, as separately indicated at FIGS. 5a and 5b, results in the antenna of the present invention wherein the phase of radiation adds in the left quadrant of the figure, as indicated, and

subtracts in the right quadrant of the figure, also as indicated. This then consequently produces a directivity of radiation wherein the phase $\beta+\alpha$ occurs in the $[+X +Y]$ quadrant and the phase $\beta-\alpha$ occurs in the $[-X +Y]$ quadrant. The illustrated radiation patterns of FIG. 5 are taken in the plane of the antennas illustrated with the different patterns and it is believed clear from this general approach to the invention that radiation in the plane of the antenna of the present invention does have a directivity in which the majority of radiation lies in a particular direction.

With regard to a mathematical analysis of the antenna of the present invention it is convenient to consider the antenna hereof, including the mirror image of the antenna beneath the ground plane, as a transmission line. Currents in such a line may be arbitrarily separated into a constant and a variable mode. In order to arrive at a far field expression there may be first considered or derived the filament currents of the antenna. The filament radiator and resistor can be considered as a two-wire line fed by a balun incorporating the image currents below the ground plane, and in this respect reference is made to FIG. 4. The surge impedance of the two wire line for an air dielectric is

$$Z_1 = 120 \cos h^{-1}(2l)/d \quad (1)$$

where $2l$ is the center spacing between the lines and d is the conductor diameter. The total current I is found from the standard transmission line equation:

$$I = I^+ e^{+jks} + I^- e^{jks} \quad (2)$$

where

I^+, I^- —incident and reflected current waves, respectively

k —phase constant, $2\pi/\lambda$

s —distance from load towards generator

The reflection coefficient ρ is defined as:

$$\rho = (Z_L - Z_1)/(Z + Z_1) \quad (3)$$

Where Z_L is twice the "end load" resistor R_L and Z_1 is defined in (1). From (2) and (3) it can be shown that:

$$I_s = I^+ [(1-\rho) \cos(ks) + j(1+\rho) \sin(ks)] \quad (4)$$

Note that I_s is the total current on the line from input to the resistor. The current flowing into the resistor is I_r , where

$$I_r = I_s|_{s=0} = I^+ (1-\rho) \quad (5)$$

If the assumption is made that I_r is constant along the resistor, then (4) and (5) completely define the current at every point on the antenna, namely:

$$I = I_s \text{ for } s > 0 \\ I = I_r \text{ for } s = 0$$

By the principle of superposition, we will now define the current as a sum of a constant and a variable term:

$$I = I_r + I_c \quad (6)$$

where

$$I_r = I^+ [(1-\rho) \cdot (\cos(ks) - 1) + j(1+\rho) \sin(ks)] \quad (7)$$

$$I_c = I^+ (1-\rho) \quad (8)$$

In effect, I_r was subtracted from I_s and then assumed to exist in the entire transmission line. In this fashion the current I_c forms a small square loop of constant magnitude, and the current I_r forms a small inverted L monopole. The resistor is eliminated, and the far field becomes the sum of two fields generated by a monopole and a loop.

Testing (7) for small arguments, after setting $I^+ = 1.0$ as a unit excitation current:

$$I_r(ks \rightarrow \epsilon) \approx j(1+\rho)\epsilon$$

where ϵ —arbitrarily small number, the term $[\cos(ks) - 1]$ converges faster to zero than does $\sin(ks)$. Hence, for small arguments:

$$\left. \begin{aligned} I_r &\approx j(1+\rho)\epsilon \\ I_c &= (1-\rho) \end{aligned} \right\} \quad (9)$$

i.e., the currents are in quadrature. Remembering now that for the same current, the far-field patterns of small loops and small monopoles are in quadrature, the patterns generated by the currents in (9) will therefore be approximately in the same phase, provided that ks remains small. This small argument approximation is the basic reason for the directive pattern of the present invention.

Two further approximations are made to determine the currents used in calculating the far field. First, the two-wire line is defined to exist from the location of the resistor to the coaxial input point; secondly, the currents over sections of this line are averaged out. The first approximation states that the wire segment emerging from the coaxial line normal to the ground plane has a phase constant which, for small length, is approximately that of the two-wire line; the second approximation substitutes a constant quantity for small changes in sinusoidal functions. Both of these approximations affect only I_r .

Letting the horizontal segment be m , and the vertical segment l , the total length s of the transmission line varies $0 \leq s \leq (l+m)$. The average value of I_r in the horizontal section is:

$$I_{r1} = \frac{1}{2}[(1-\rho)(\cos km - 1) + j(1+\rho)\sin(km)] \quad (10)$$

In the vertical section the average current is:

$$I_{r2} = \frac{I_r(s=l+m) + I_r(s=m)}{2}$$

$$I_{r2} = \frac{1}{2}(1-\rho)[\cos[k(l+m)] + \cos(km) - 2] + j(1+\rho)[\sin[k(l+m)] + \sin(km)] \quad (11)$$

The constant term is as in (8):

$$I_r = (1-\rho)$$

The currents in (10), (11) and (8) may be employed to determine the far field expressions.

In order to derive an expression for the far field radiation of the present invention it is convenient to establish a coordinate system such as illustrated, for example, in FIG. 3. It will be seen from reference to FIG. 3 that a three-dimensional x, y, z -coordinate system is set forth therein with the ground plane in the xz -plane and the antenna of the present invention located in the xy -plane. In this illustration, as employed in the following derivations, the feed point of the antenna, wherein the radiator passes through the ground plane, is taken to be a distance $m/2$ from $y=0$ in the xz -plane and the extent of the antenna from this plane to be defined as l in conformity with prior derivations wherein the term l identified the extent of the L-shaped antenna from the ground plane. In addition to the foregoing, the conventions employed hereafter include the angle Φ in the yx -plane and the polar angle θ about the Z -axis. These angles are plainly marked in FIG. 3. In order to understand the following far field expression derived as a representation of the radiation of the present invention, it is noted that the current is considered to be flowing out of the coordinate $m/2, 0, 0$ toward the resistor R_L of FIG. 3. Following the previously identified conventions, the current I_r flows from the above-noted point of the antenna in the positive y -direction and thence in the negative x -direction. Consequently the filament current vectors of the antenna become, neglecting I_c , are:

$$\begin{aligned} I_y &= I_{r2} \\ I_x &= -I_{r1} \end{aligned} \quad (12)$$

where, U_y, U_x are cartesian unit vectors.

The delayed vector potentials for the far field (noting that the current density I is identical to the linear current I for a constant diameter conductor):

$$A_y = \frac{\mu e^{-jkr}}{4\pi r} \int_0^{+\rho} I_y e^{jkxy} U_y dy \quad (13)$$

$$A_x = \frac{\mu e^{-jkr}}{4\pi r} \int_{-\frac{m}{2}}^{\frac{m}{2}} I_x e^{jkx} U_x dx \quad (14)$$

Note that integration proceeds along the filament from the input ($x=m/2, y=0$) to the resistor ($x=-m/2, y=l$) Furthermore:

$$g_y = U_x(m/2) + U_y y$$

$$g_x = U_x x + U_y l$$

$$U_r = U_x \sin \theta \cos \Phi + U_y \sin \theta \sin \Phi + U_z \cos \theta$$

Letting the current terms I_x and I_y be constants by (10) and (11), (13) and (14) become, respectively:

$$A_y = \frac{\mu I_y e^{-jkr}}{4\pi r} e^{jk \frac{m}{2} \sin \theta \cos \Phi} \int_0^{\rho} e^{jk y \sin \theta \sin \Phi} dy \quad (15)$$

$$A_x = \frac{\mu I_x e^{-jkr}}{4\pi r} e^{jk P \sin \theta \sin \Phi} \int_{-\frac{m}{2}}^{\frac{m}{2}} e^{jk x \sin \theta \cos \Phi} dx \quad (16)$$

5 If we take the image currents into account, and carry out the integration:

$$A_y = \frac{\mu I_y l e^{-jkr}}{2\pi r} e^{jk \frac{m}{2} \sin \theta \cos \Phi} \frac{\sin(kP \sin \theta \sin \Phi)}{(kP \sin \theta \sin \Phi)} \quad (17)$$

$$A_x = \frac{-j\mu I_x m e^{-jkr} \sin(kP \sin \theta \sin \Phi) \sin\left(k \frac{m}{2} \sin \theta \cos \Phi\right)}{2\pi r \left(k \frac{m}{2} \sin \theta \cos \Phi\right)} \quad (18)$$

In the foregoing equations (17) and (18) the terms $\sin(kl \sin \theta \sin \Phi)/(kl \sin \theta \sin \Phi)$ may be disregarded for small arguments of km and kl . Considering this point further, it is noted that by substituting the term x for $kl \sin \theta \sin \Phi$, the expressions which are disregarded may be considered as $(\sin x)/x$ which can be expanded as follows:

$$(\sin x)/x = 1 - (x^2/3!) + \dots$$

The quadratic approximation of this relationship under the conditions wherein the equation shall not substantially vary from that expressed by more than 5 percent is

$$(\sin x)/x = 1 - x^2/3! = 1 - 0.05$$

From this it is then possible to derive that $x = \pm 0.56$ and consequently that the length of one portion of the antenna or filament radiator shall be no more than 0.09λ for a 1:1 ratio between height and length of the antenna radiator and λ is the free space wavelength at the operating frequency of the antenna. Considering that the aspect ratio i.e., the length to height of the radiator, which may be expressed as l/m , is 1:1, it then follows that the maximum length of the filament radiator is of the order of 0.20λ . In order to normalize this to operation of the present invention it is appropriate to consider that the highest operating frequency of the filament radiator of the antenna, and such is hereinafter considered to be the case. It will of course be appreciated that arguments can be presented with regard to the proper delineation of the term "electrically small" particularly as related to a resonant antenna, however, in the present invention it is herein stated that the total filament radiator length shall be no greater than 0.20λ , wherein λ_h is the free space wavelength of the highest operating frequency of the antenna.

Considering further equation (17) above, it is noted that the phase term may be disregarded.

Constant terms common to all field quantities, such as $\mu e^{jkr}/4\pi r$, and later $(-jw)$, are also neglected:

$$\left. \begin{aligned} A_y &\approx 2I_y l \\ A_x &\approx -2jI_x m \sin(kl \sin \theta \sin \Phi) \end{aligned} \right\} \quad (19)$$

Transforming to the spherical coordinates:

$$A_\theta = -2jI_x \sin(kl \sin \theta \sin \Phi) \cos \Phi \cos \theta + 2I_y l \sin \Phi \cos \theta \quad (20)$$

$$A_\phi = +2jI_x m \sin(kl \sin \theta \sin \Phi) \sin \Phi + 2I_y l \cos \Phi \quad (21)$$

From Maxwell's equations we note that, for the far field case:

$$\left. \begin{aligned} E_\theta &= -j\omega A_\theta \\ E_\phi &= -j\omega A_\phi \end{aligned} \right\} \quad (22)$$

60 The total Φ -component will also include the field generated by the constant term I_c :

$$E_\phi(\text{loop}) = jklm(1-\rho) \sin \theta \quad (23)$$

By making the proper substitution into equation (22) it is possible to obtain a relationship for the total E -field in terms of the real $Re(E_\phi)$ and imaginary $Im(E_\phi)$ portions thereof.

$$E_\theta = Re(E_\theta) + jIm(E_\theta) = + \frac{m(1+\rho) \sin(km) \sin \Phi \sin(kP \sin \theta \sin \Phi) + l(1-\rho) \cos \Phi [\cos[k(P+m)] + \cos(km) - 2]}{2} \quad (24)$$

$$Im(E_\phi) = - \frac{m(1-\rho)(\cos km - 1) \sin \Phi \sin(kP \sin \theta \sin \Phi) + (1+\rho)l \cos \Phi [\sin[k(P+m)] + \sin(km)] + klm(1-\rho) \sin \theta}{2} \quad (25)$$

In the same fashion:

$$E_{\theta} = Re(E_{\theta}) + jIm(E_{\theta}) Re(E_{\theta}) = \\ (1-\rho)l \sin \phi \cos \theta [\cos [k(P+m)] + \cos (km) - 2] - \\ m(1+\rho) \cos \phi \cos \theta \sin (km) \sin (kP \sin \theta \sin \phi) \quad (26)$$

$$Im(E_{\theta}) = + \\ l(1+\rho) \sin \phi \cos \theta [\sin [k(P+m)] + \sin (km)] + \\ m(1-\rho) [\cos (km) - 1] \cos \phi \cos \theta \sin (kl \sin \theta \sin \phi) \quad (27)$$

As set forth above, the composite radiation pattern of the antenna of the present invention is reinforced in one direction in the principle plane of the antenna and electrically interferes in the other direction or quadrant of the principle plane. Upon the filament the currents add algebraically and the electromagnetic field generated by these currents adds vectorially. The principle of superposition applies under the assumptions that there are employed linear passive elements in an isotropic linear medium. Beam shaping is achieved by controlling the amount of energy the loop and the monopole radiate. This control is in fact executed by the magnitude of the loading resistor R_L for a given filament thickness and height. It is believed to be apparent that as the resistance R_L is varied from a very high resistance value to a very low resistance value the radiation pattern in the principle plane will vary from a monopole pattern through stages of beam tilting to that of a loop antenna pattern. Reference is made at this point to FIGS. 8 and 9 of the present application where there is illustrated the relationship between calculated principle plane radiation patterns of $E\Phi$ vs. ρ (reflection coefficient). In effect beam control in the present invention comprises the attainment of a front to back ratio (F/B) which is a measure of the capability of the antenna of the present invention to radiate more energy into the preferred direction than into another direction in the principle field of the antenna. It is particularly noted that the F/B ratio is under the control of the resistor R_L via the parameter ρ , as clearly established by FIGS. 8 and 9 hereof.

As an aside to the foregoing it is noted that the previous calculations imply an infinite flat ground plane. In practice it is realized that such a ground plane does not exist. The limited size of a practical ground plane tends to reduce the level of the pattern in the $\Phi=0^\circ$ and $\Phi=180^\circ$ direction. An actual application of the present invention provides for control of the directivity of the radiation from the antenna of the present invention.

The equations defining the antenna radiation patterns are set forth above under equations (24), (25), (26), and (27). Insofar as a practical design equation for the filament radiator of the present invention is concerned, it may be considered that:

$$\text{Cosh}^{-1} \left(\frac{2l}{d} \right) = \frac{R\pi}{\gamma} \cdot \frac{(\rho-1)}{(\rho+1)}$$

wherein l = the length of vertical filament segment in the y direction of FIG. 3, d = filament diameter, R = value of resistor 19, ρ = parameter which determines F/B ratio, γ = medium impedance (377-ohm for air).

In order to employ the design equation set forth above in practice the parameters l and d are defined and then by reference to FIGS. 8 and 9 of the drawings hereof a desired F/B ratio is determined in order to yield a desired ρ . The equation set forth immediately above will then give the necessary magnitude of the resistance R . A practical equation resulting from the foregoing is that in which $\rho=0$ so that for a minimum of a 6 db F/B there results the equation

$$2l/d = \cos h(R/120)$$

A matter of practical importance is the relationship of the length m of the antenna sector 13 to the length l of antenna sector 12 of the invention. While it may be postulated that the relationship of these values could or should be 1:1 it has been found through experimentation that the relationship, herein termed the aspect ratio, is preferably of the order of 2:1 wherein the portion of the antenna parallel to the ground

plane is of the order of twice the length of portion of the antenna perpendicular to the ground plane.

There is produced by the antenna of the present invention a radiation pattern in the principle plane of the antenna which is directional. There is illustrated in FIG. 6 a plot of relative power radiated at different angles in the E -plane or principle plane of the antenna for a typical end loaded filament antenna in accordance with the present invention. It will be seen from this figure that maximum power in this instance is radiated at a tilt angle to a perpendicular through the center of the antenna and that such angle is of the order of 41° .

It will be seen from the foregoing description of a single preferred embodiment of the present invention and derivation of relationships in accordance with this invention, that the end-loaded filament antenna hereof has directional properties of predeterminable degree. The structure of this antenna is maintained extremely small, and the structure is extremely simple. The illustrated embodiment of the present invention provides a tilted radiation pattern in the principle plane of the filament radiator, and the directivity of radiation is dependent upon the resistance of the end-loading filament in relation to the extent of the filament above the ground plane and the diameter or thickness of the filament radiator itself.

The embodiment of the invention described above comprises a filamentary radiator having an L-shape with the portions being at right angles to each other. The far-field summation of radiation from this configuration is substantially the same as would be produced from a filamentary radiator extending at an angle between the two ends of the radiator portions of FIG. 1. Substantially the same theoretical considerations are involved as those presented above. Thus in FIG. 7 such a configuration is shown wherein a radiator 31 is shown to extend substantially from a ground plane 32 at an angle upwardly from an opening therein to a termination at the top of a small passive resistor 33 having the bottom end connected to this ground plane. Such a radiator may be energized in the same manner as the radiator of FIG. 1, as by forming the radiator as an extension of the central conductor of a coaxial cable having the outer conductor thereof connected to the ground plane. It will be appreciated that radiation from such a filament 31 may be considered as emanating from the hypotenuse of a triangle with the vertical and horizontal portions thereof, as indicated by dashed lines in FIG. 5, and occupying substantially the same location as the legs 12 and 13 of the radiator of FIG. 1. Thus, insofar as far-field summation of radiation is concerned, the embodiment of the invention illustrated in FIG. 7 is substantially the equivalent of that illustrated in FIG. 1.

With an embodiment such as shown in FIG. 7, consideration must be given, however, to fringe inductance and capacitance at the feed end of the radiator. With the radiator inclined, as illustrated, there results a smaller angle between the radiator and the feed cable and lesser spacing between the radiator and outer conductor of such cable on one side of the radiator. Thus this embodiment of the invention might be considered as one extreme variation of the configuration of FIG. 1. Clearly, intermediate configurations are also possible such as, for example, by extending the radiator upward some distance from the ground plane and then bending it at an angle less than 90° to vertical for inclined extension to the top of the resistor 33. Clearly, also it is possible for the radiator to be curved in the principle plane rather than having a sharp angle bend, although it is to be appreciated that the more complex the form of the radiator, the more difficult it is to theoretically determine the radiation pattern and exact direction of maximum radiation. It is also to be noted that the extremely short length of the radiator militates against complex configurations. Furthermore, any extension above the upper end of the resistor 33 will cause some radiation to occur toward the right of FIG. 7 and thus to produce a double-lobe radiation pattern which is not desired for a unidirectional antenna.

Although the embodiment illustrated in FIG. 1 of the drawings is considered to be a preferred embodiment of the present invention it is to be appreciated that variations in configuration of the filament radiator hereof within the limitations

set forth above are possible. The present invention does provide an electrically short antenna having directional radiation properties and thus combines the advantages of directional antennas and of miniaturized antenna structure.

Although the present invention has been described above in connection with particular preferred embodiments thereof, it is not intended to limit the invention by the exact terms of the foregoing description or details of illustration. Reference is made to the appended claims for a precise delineation of the true scope of this invention.

I claim:

1. An improved filament antenna comprising:
 - a. means defining a ground plane,
 - b. an electrically small filament having a length in the range of 0.05 to 0.20 free-space wavelength of the shortest wavelength of radiation propagated or received by the antenna,
 - c. a small passive resistor connecting one end of said filament to said ground plane, and
 - d. feed means engaging the other end of said filament in the vicinity of said ground plane for passing a current through said filament, said filament extending upwardly from said ground plane to said resistor in a single principal plane for establishment of a radiation beam having a maximum in the principal plane and tilted away from the resistor.
2. The antenna of claim 1 further defined by said feed means engaging said filament at a distance along the ground plane from the electrical connection of resistor and ground plane, whereby said filament extends along said ground plane and spaced therefrom.
3. The antenna of claim 1 further defined by said filament having a length substantially equal to 0.10 wavelength at the highest operating frequency of the antenna.
4. The antenna structure of claim 1 further defined by said filament extending no further from the ground plane than the height of the passive resistor.
5. The antenna of claim 1 further defined by said filament having a first section extending substantially perpendicularly to said ground plane and a second contiguous section extending substantially parallel to said ground plane into connection with the top of said resistor and the length of the second section being substantially twice as long as the length of the first section.
6. The antenna of claim 1 having the filament thereof inclined with respect to said ground plane from the feed

means to the top of said resistor.

7. An improved directional antenna comprising means defining an electrically conducting ground plane, an L-shaped radiator having a total length no greater than 0.20 wavelength and contiguous first and second sections substantially perpendicular to each other, means defining a feed point at said ground plane and engaging the ground plane and engaging a first section of said radiator out of contact with the ground plane for applying energization between radiator and ground plane, said radiator having the first section extending substantially normal to the ground plane at the feed point and the second section substantially parallel to the ground plane, and an end-loading resistor connected to said ground plane and extending therefrom into connection with the free end of the second section of said radiator in the plane of said radiator, whereby said antenna has a radiation pattern with a maximum in the plane of the radiator and directed away from said resistor.
8. The antenna of claim 7 further defined by the relationship

$$2l/d = \cos h(R/120)$$

wherein l is the length of said second section, d is the diameter of the filament and R is the resistance value of the end-loading resistor.

9. An improved filamentary directional antenna comprising means defining a ground plane, a filamentary radiator having a first portion extending from said ground plane and a contiguous second portion of length extending along the ground plane out of contact therewith, and an end-loading impedance of resistance R connected between said ground plane and the free end of said second radiator portion, with the relationship between filament parameters being substantially defined by the relationship:

$$\cosh^{-1}\left(\frac{2l}{d}\right) = \frac{R\pi(\rho-1)}{\gamma(\rho+1)}$$

wherein d is the filament diameter, l is the filament length, γ is the medium impedance of the atmosphere surrounding the antenna and ρ is the reflection coefficient of the antenna.

50

55

60

65

70

75