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United States Patent [19]

Craven et al.

[11] **Patent Number: 5,654,723**

[45] **Date of Patent: Aug. 5, 1997**

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[54] **CONTRAWOUND ANTENNA**

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[73] Assignee: **West Virginia University**, Morgantown, W. Va.

[21] Appl. No.: **483,200**

[22] Filed: **Jun. 7, 1995**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 992,970, Dec. 15, 1992, Pat. No. 5,442,369.

[51] **Int. Cl.**^{6} **H01Q 11/12**

[52] **U.S. Cl.** **343/742**; 343/744; 343/866

[58] **Field of Search** 343/742, 743, 343/744, 788, 866, 867, 870, 840, 895

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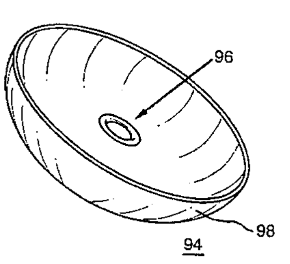
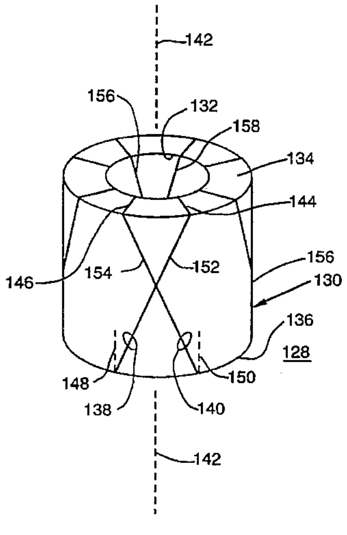
Primary Examiner—Donald T. Hajec
Assistant Examiner—Tan Ho
Attorney, Agent, or Firm—Arnold B. Silverman; Kirk D. Houser; Eckert Seamans Cherin & Mellott, LLC

[57] **ABSTRACT**

An antenna is disclosed that has windings that are contrawound in segments on a toroid form and that have opposed currents on selected segments. An antenna is disclosed that has one or more insulated conductor circuits with windings that are contrawound around and over a surface, such as a spherical surface, a generally spherical surface, a multiply connected surface, a toroidal surface, or a hemispherical surface. The insulated conductor circuits may form one or more endless conductive paths around and over the surface. The windings may have a helical pattern, a generally helical pattern, a partially helical pattern, a poloidal peripheral pattern or may be constructed from a slotted conductor on the toroid. Poloidal loop winds are disclosed with a toroid hub on a toroid that has two plates that provides a capacitive feed to the loops, which are selectively connected to one of the plates.

41 Claims, 26 Drawing Sheets





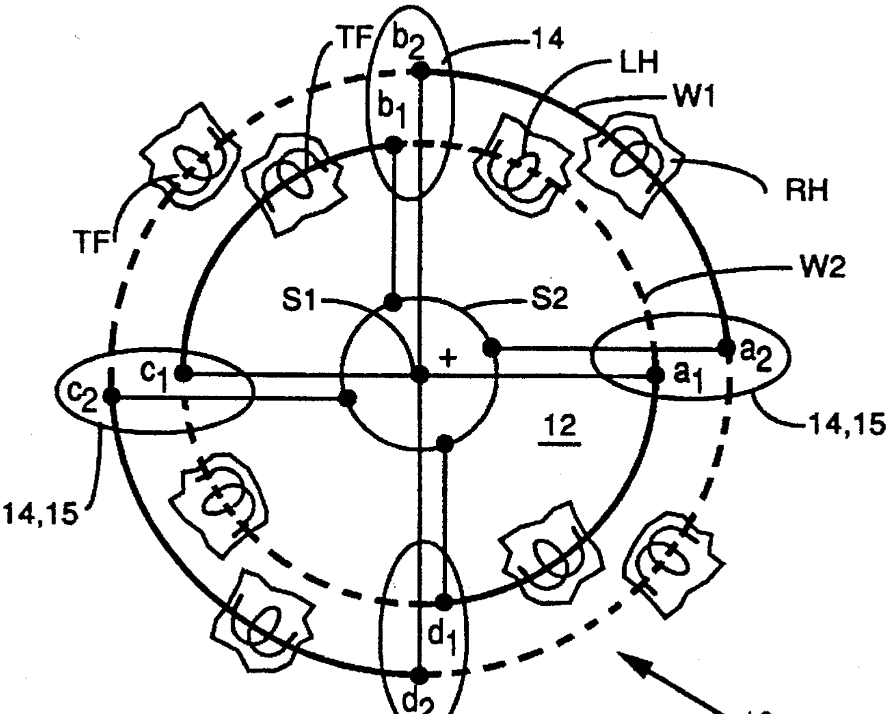


FIG. 1

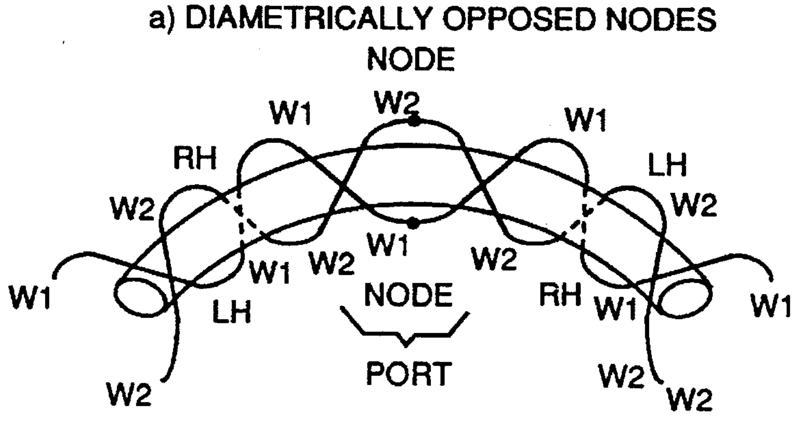
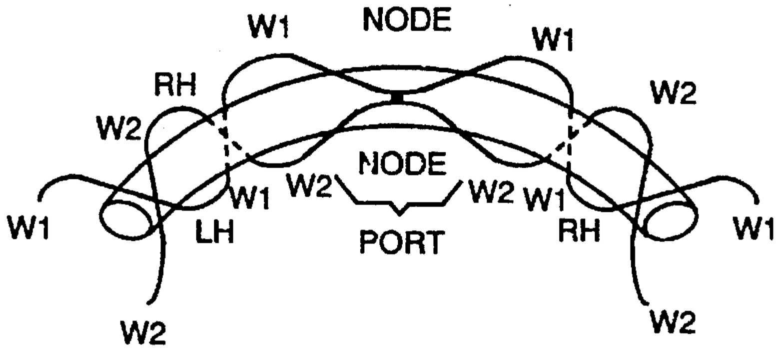


FIG. 2



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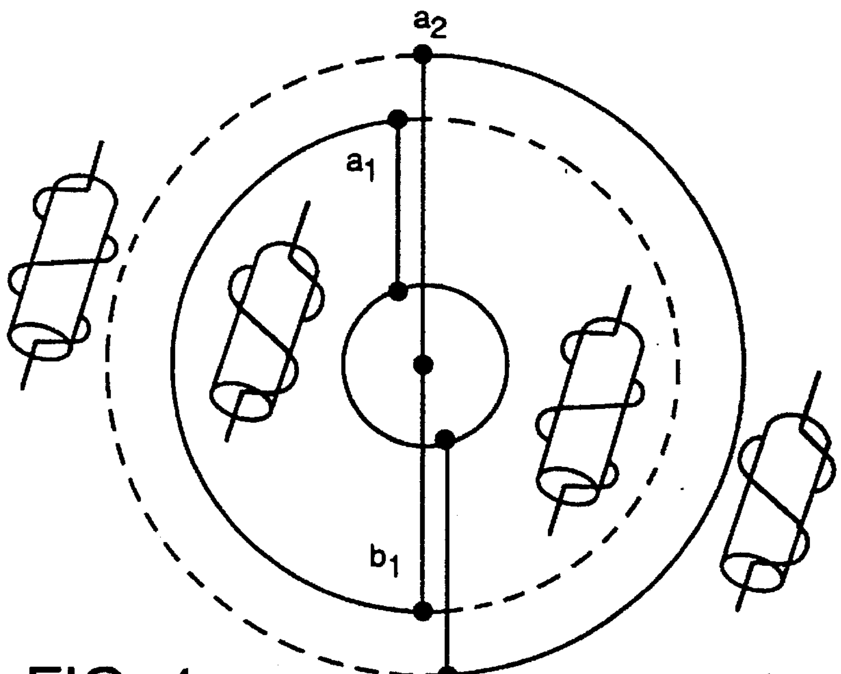

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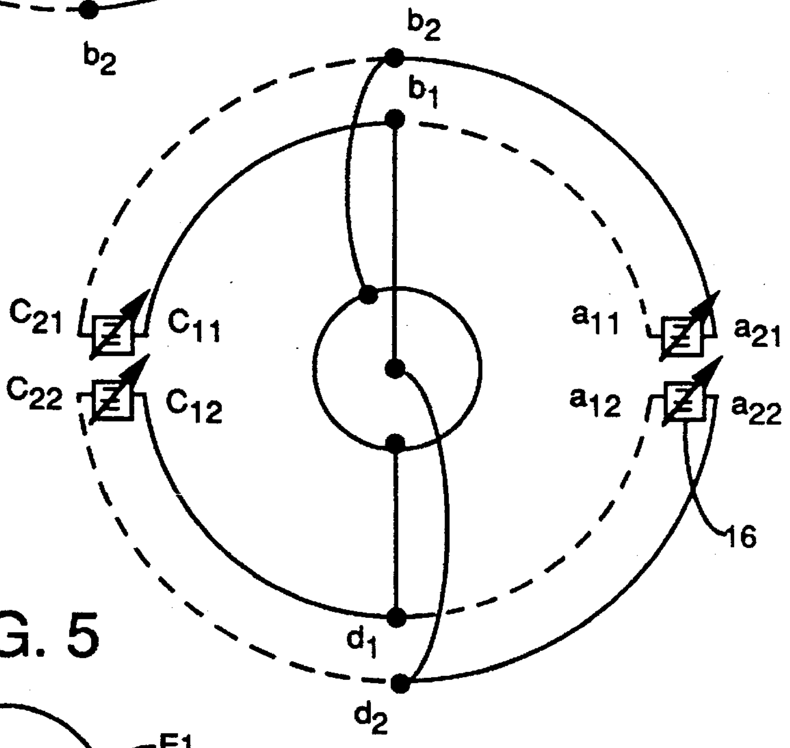

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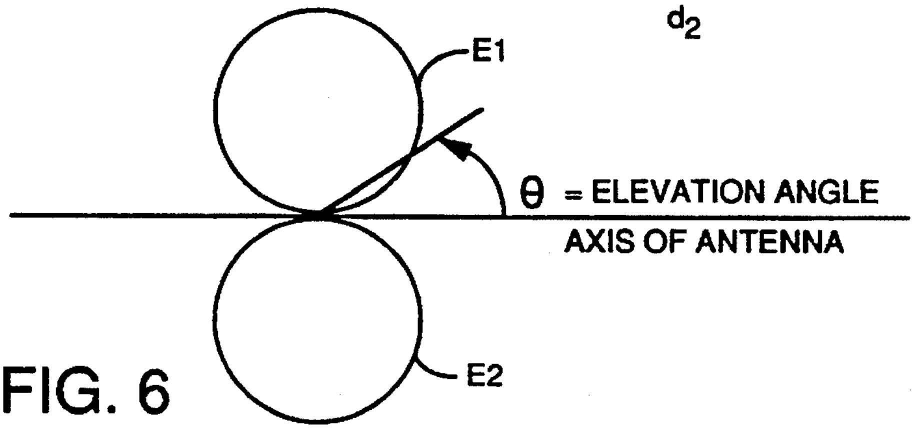

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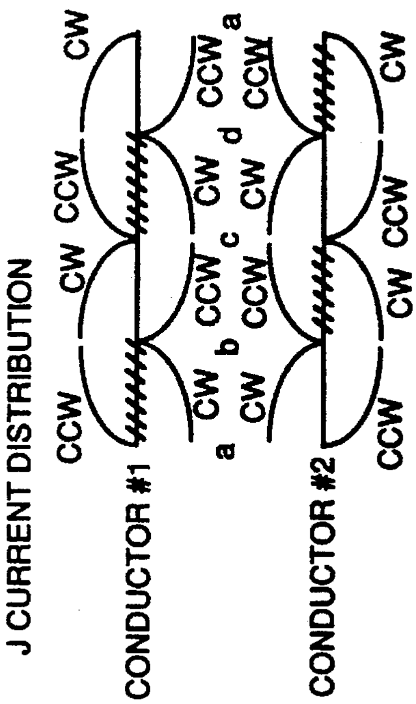

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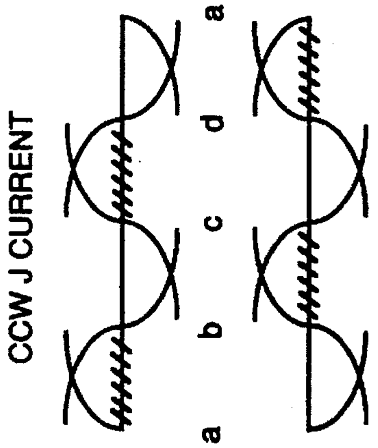

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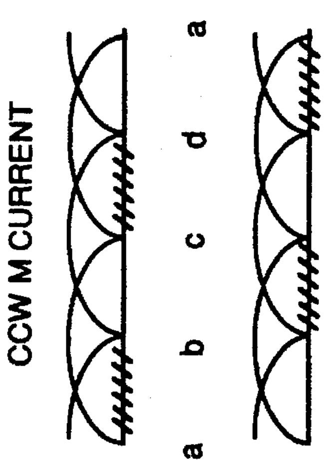

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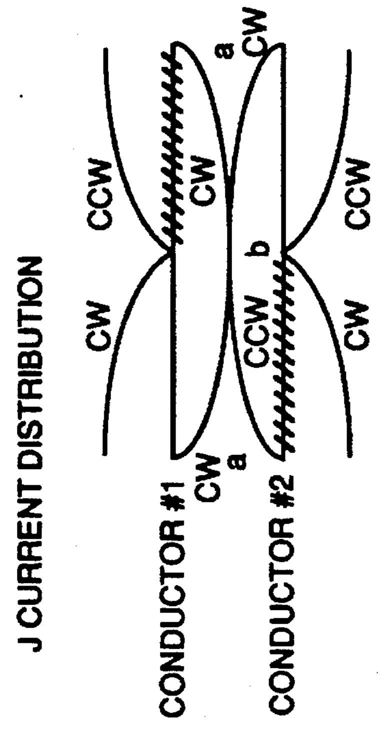

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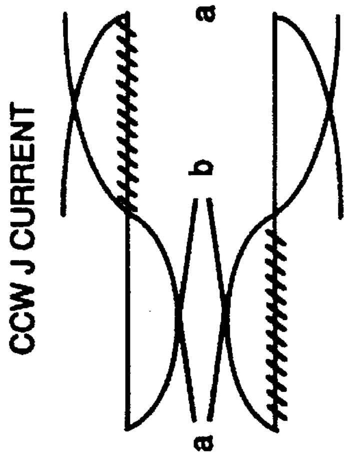

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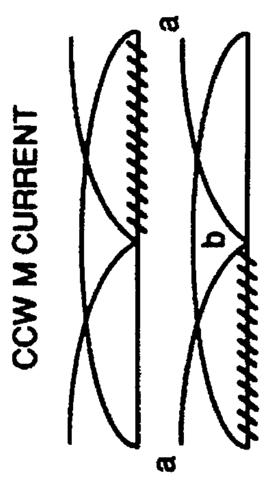

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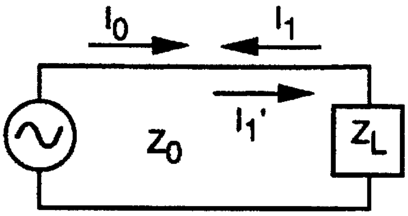
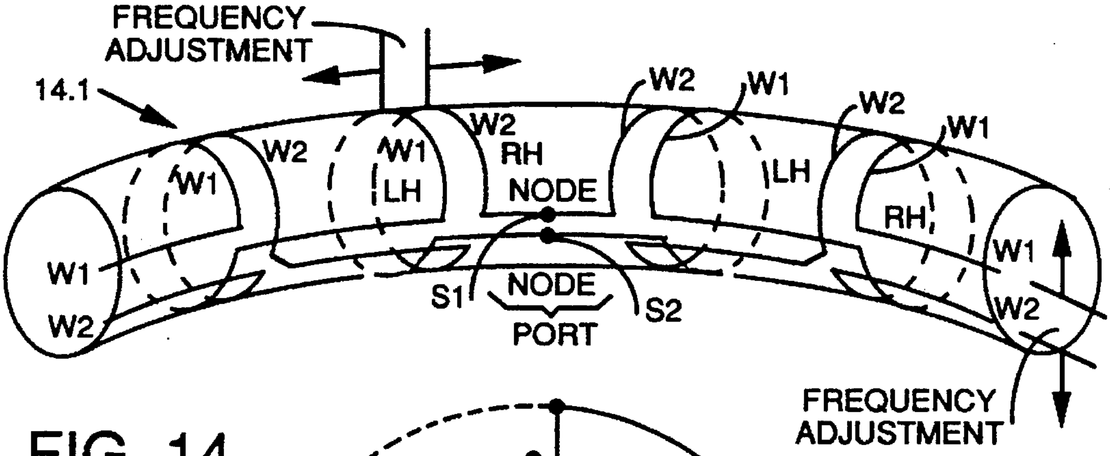


FIG. 13 PRIOR ART



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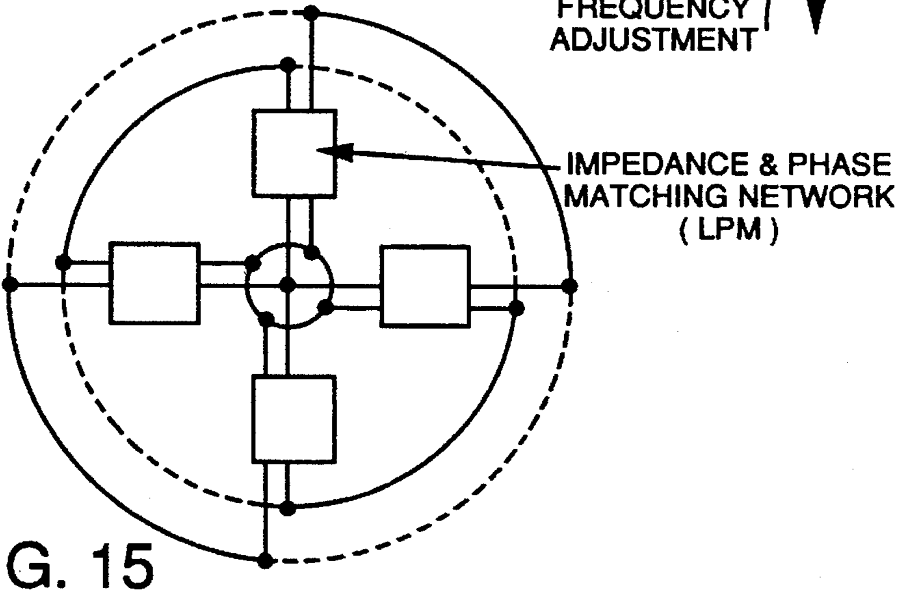

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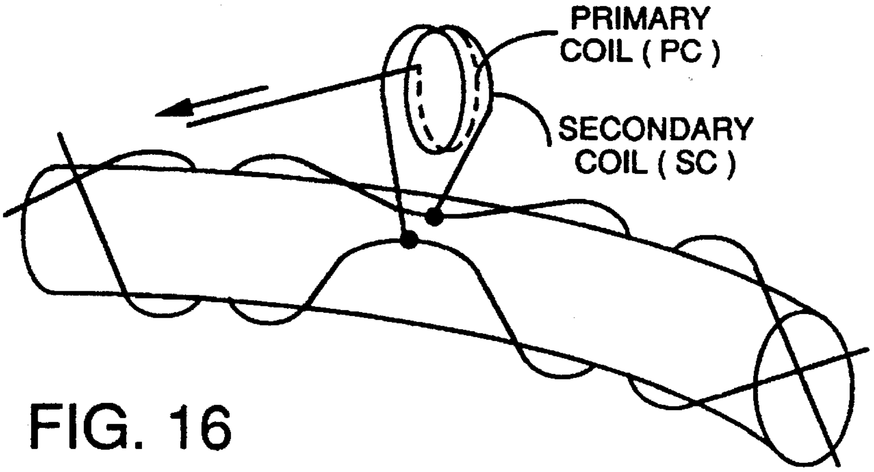

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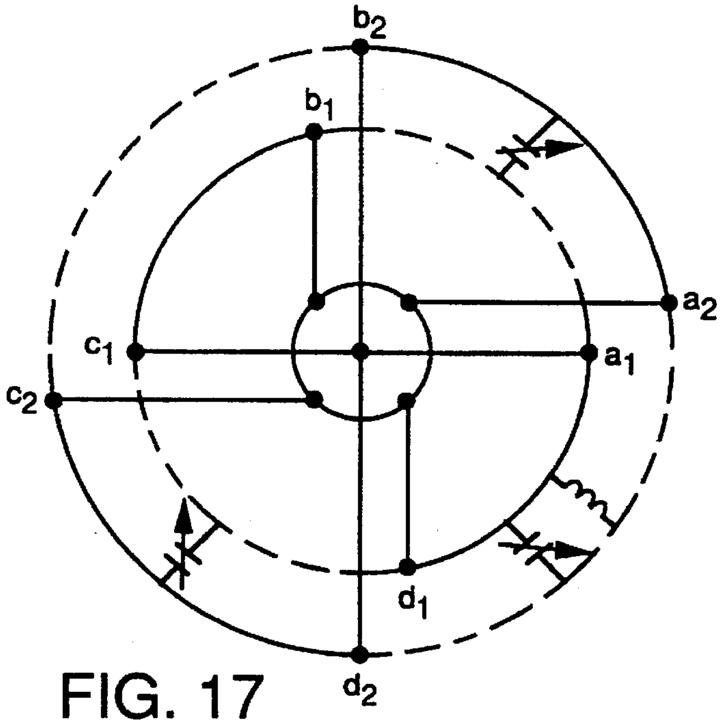

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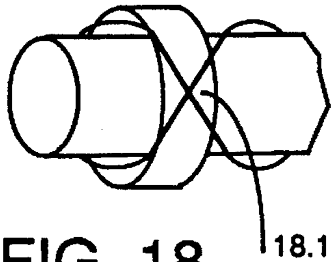

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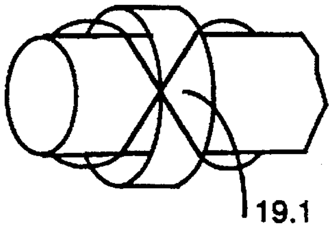

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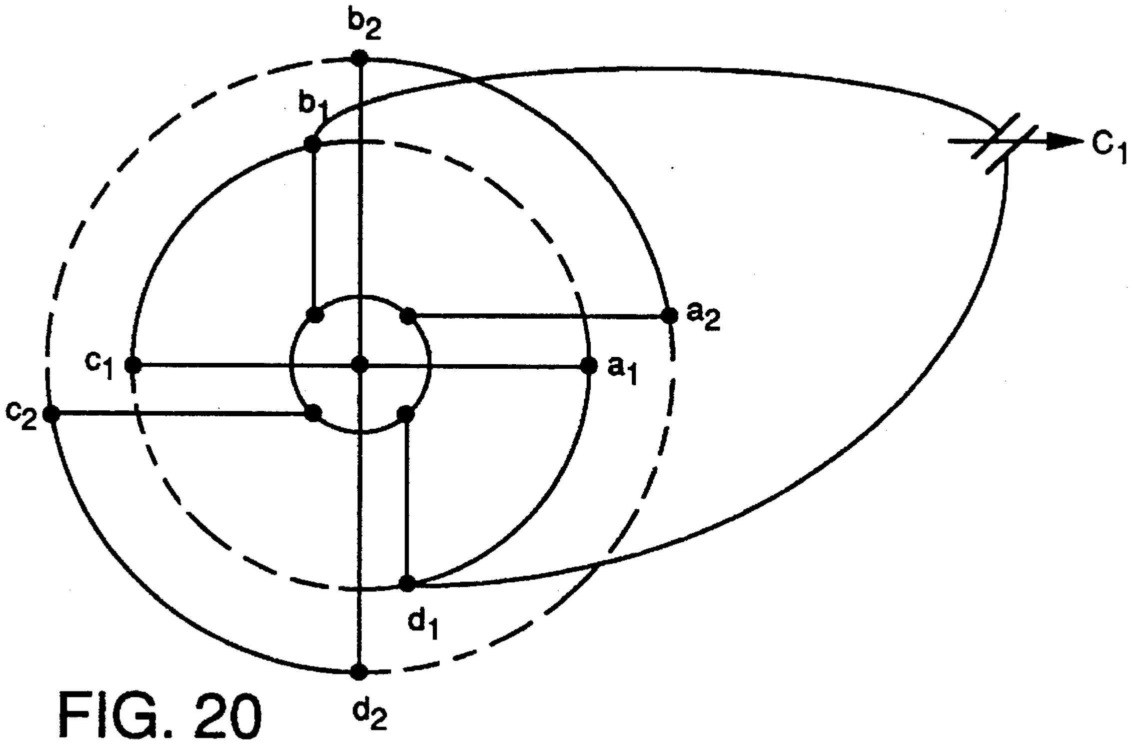

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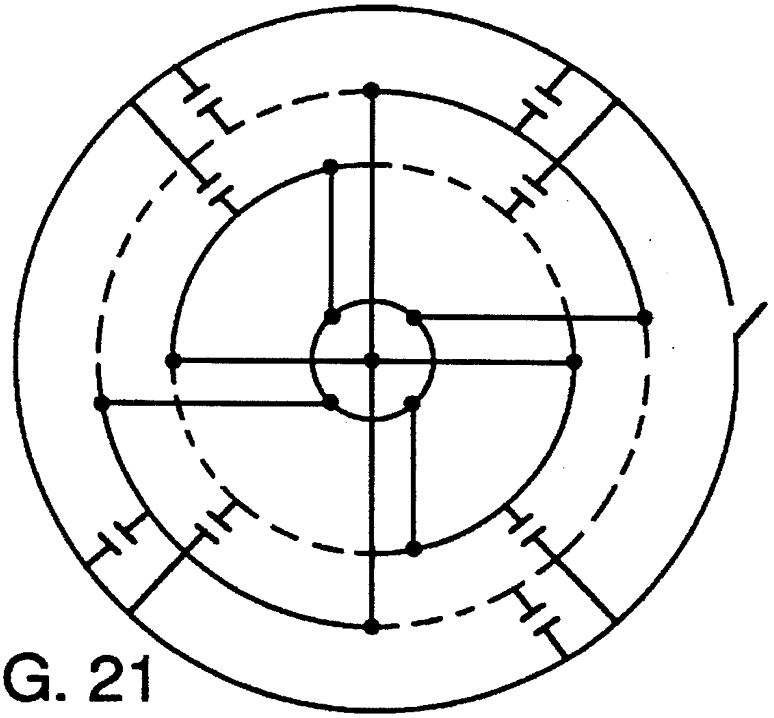

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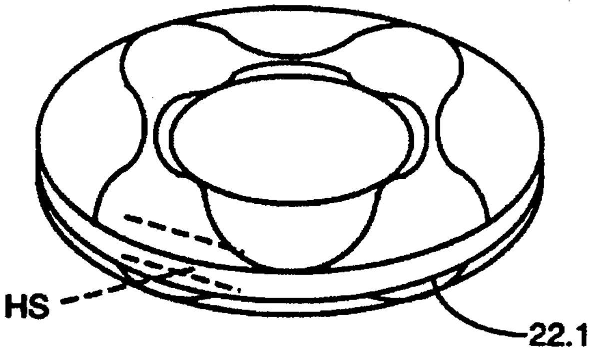

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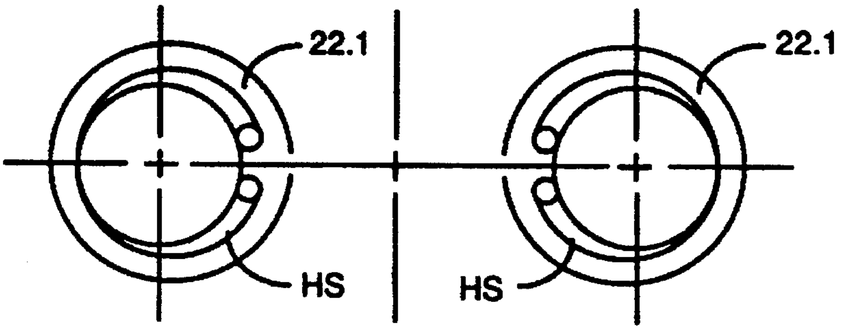

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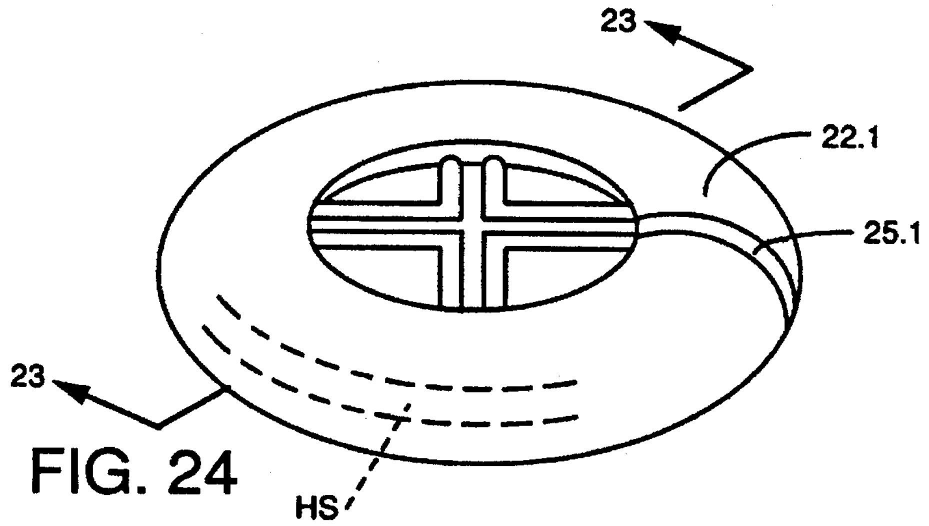

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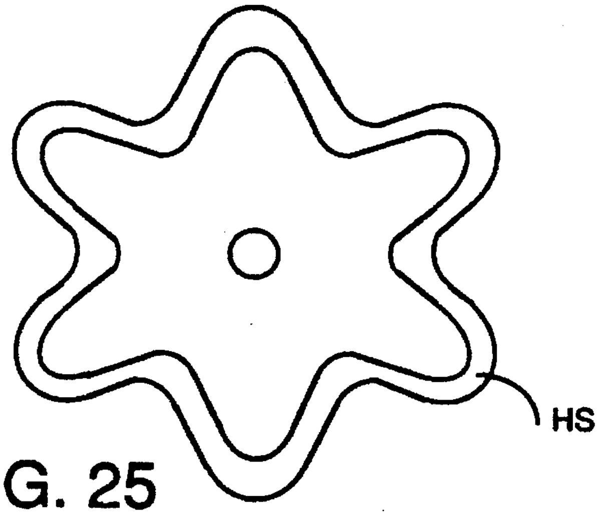

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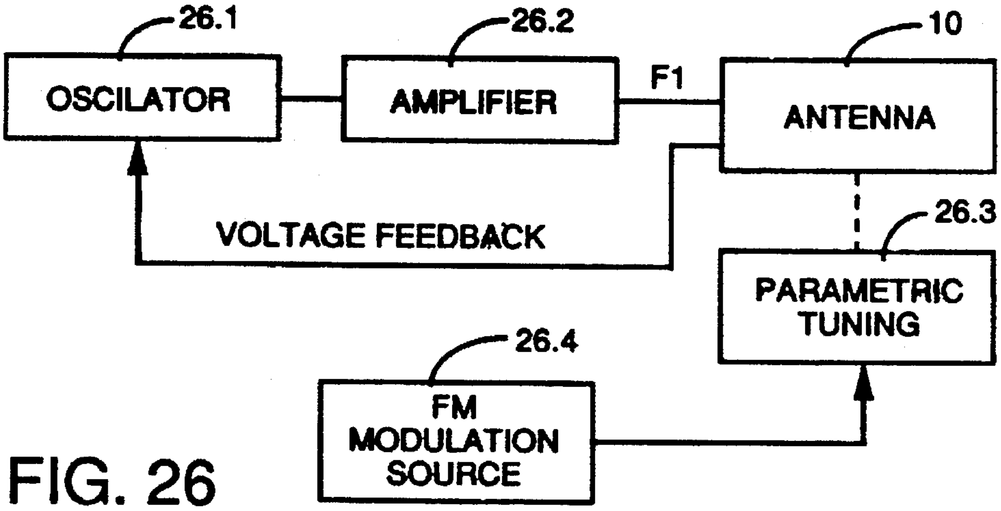

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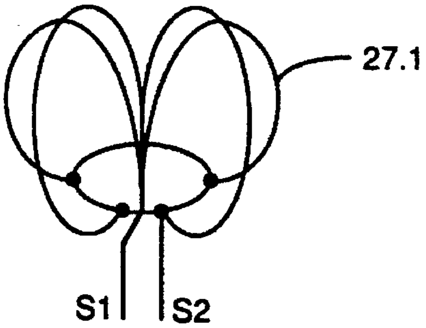

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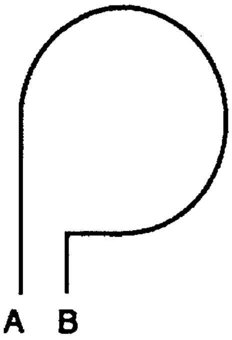

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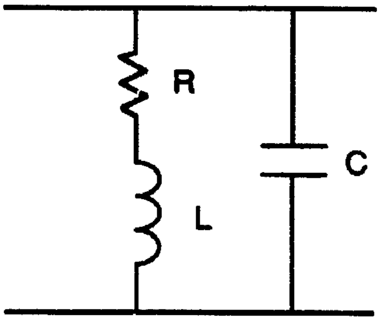

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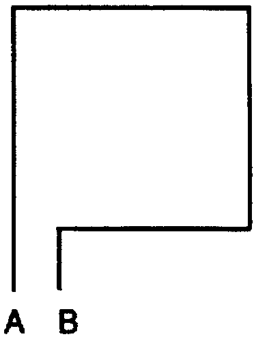

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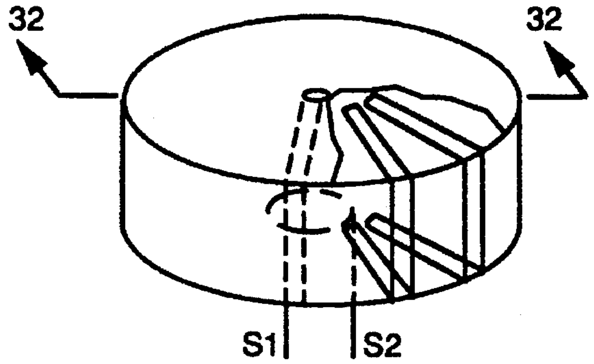

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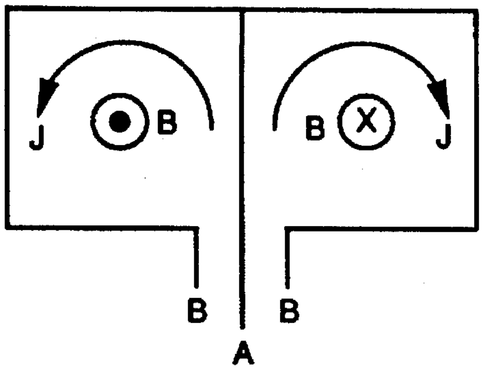

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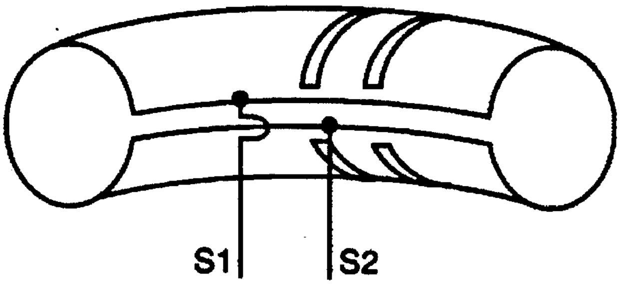

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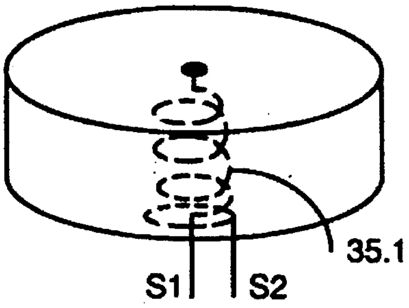
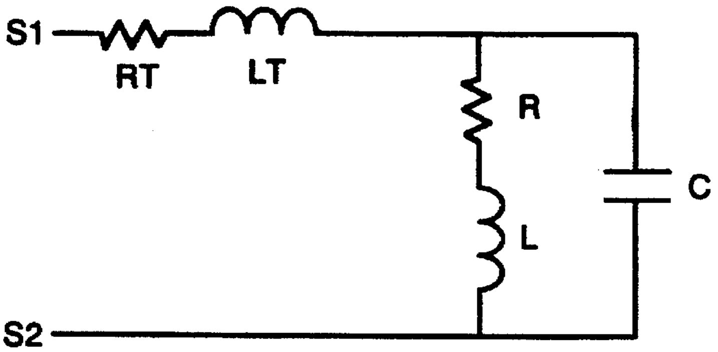


FIG. 34



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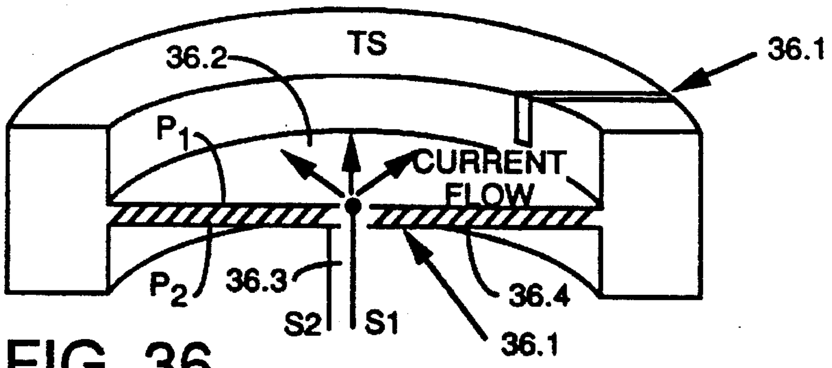

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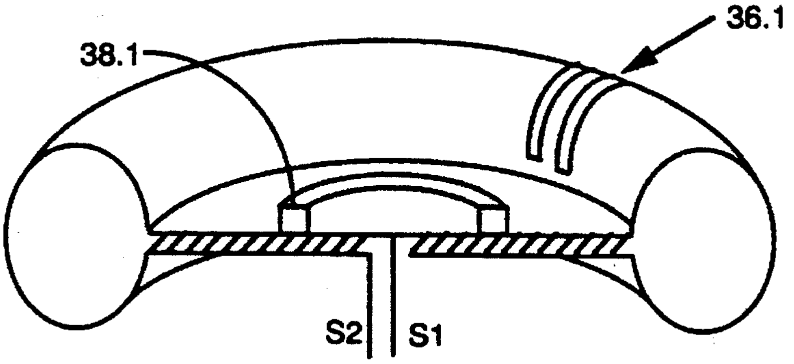

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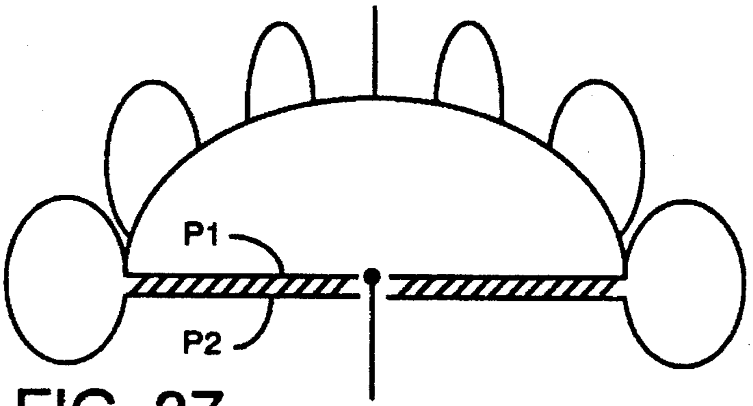

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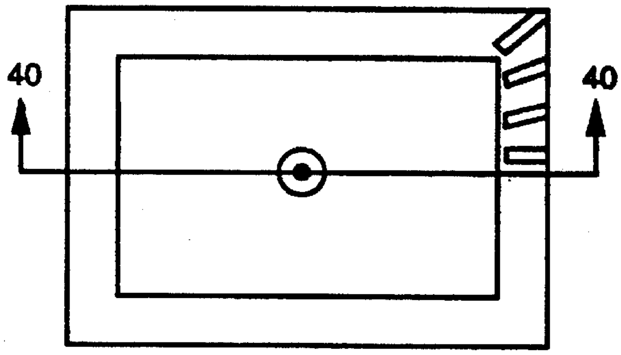

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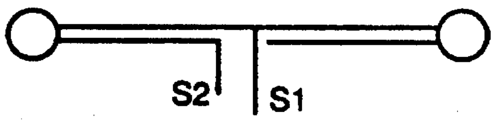

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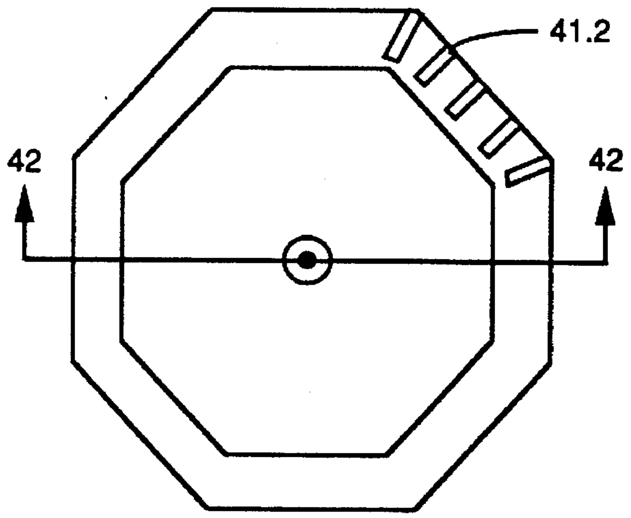

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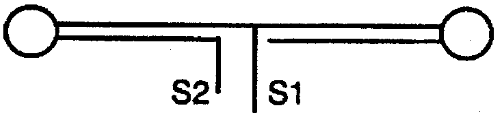

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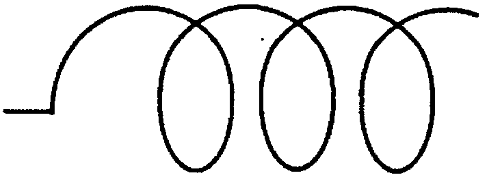

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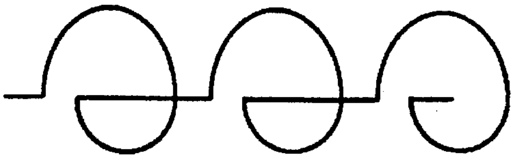

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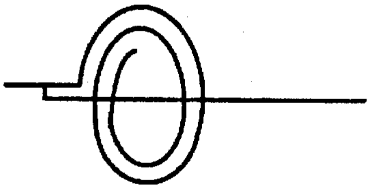

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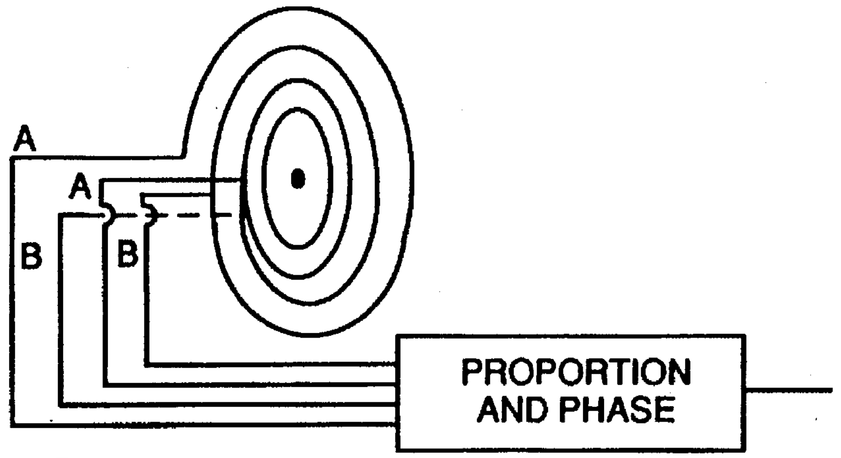

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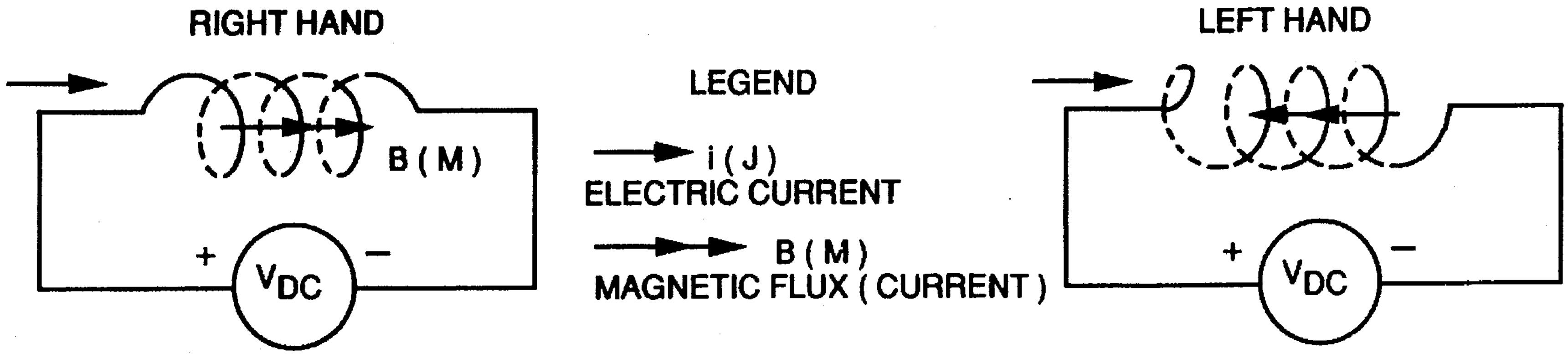

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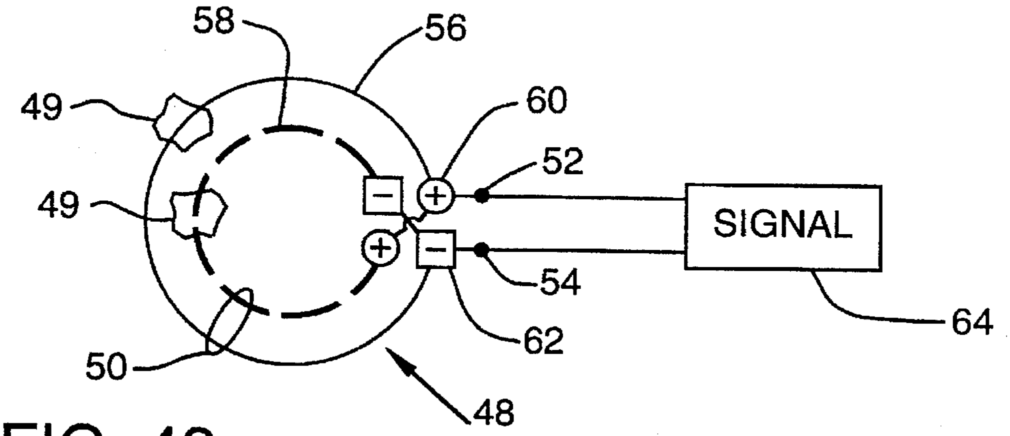

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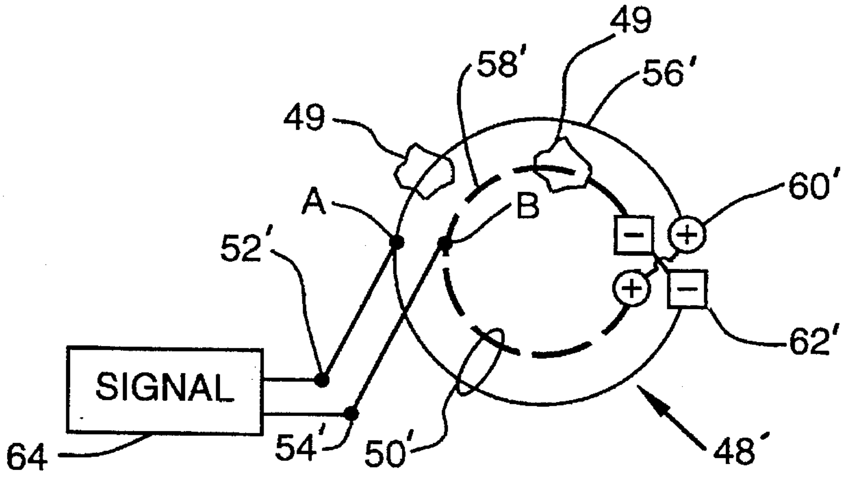

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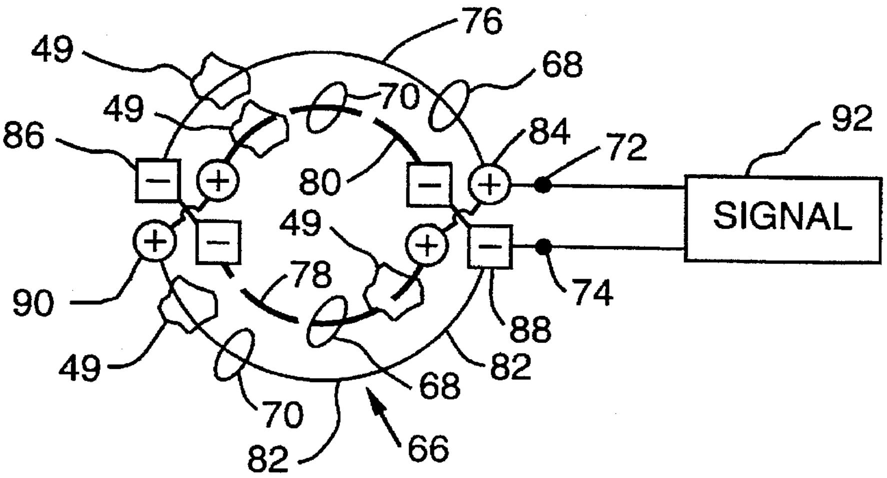

FIG. 50

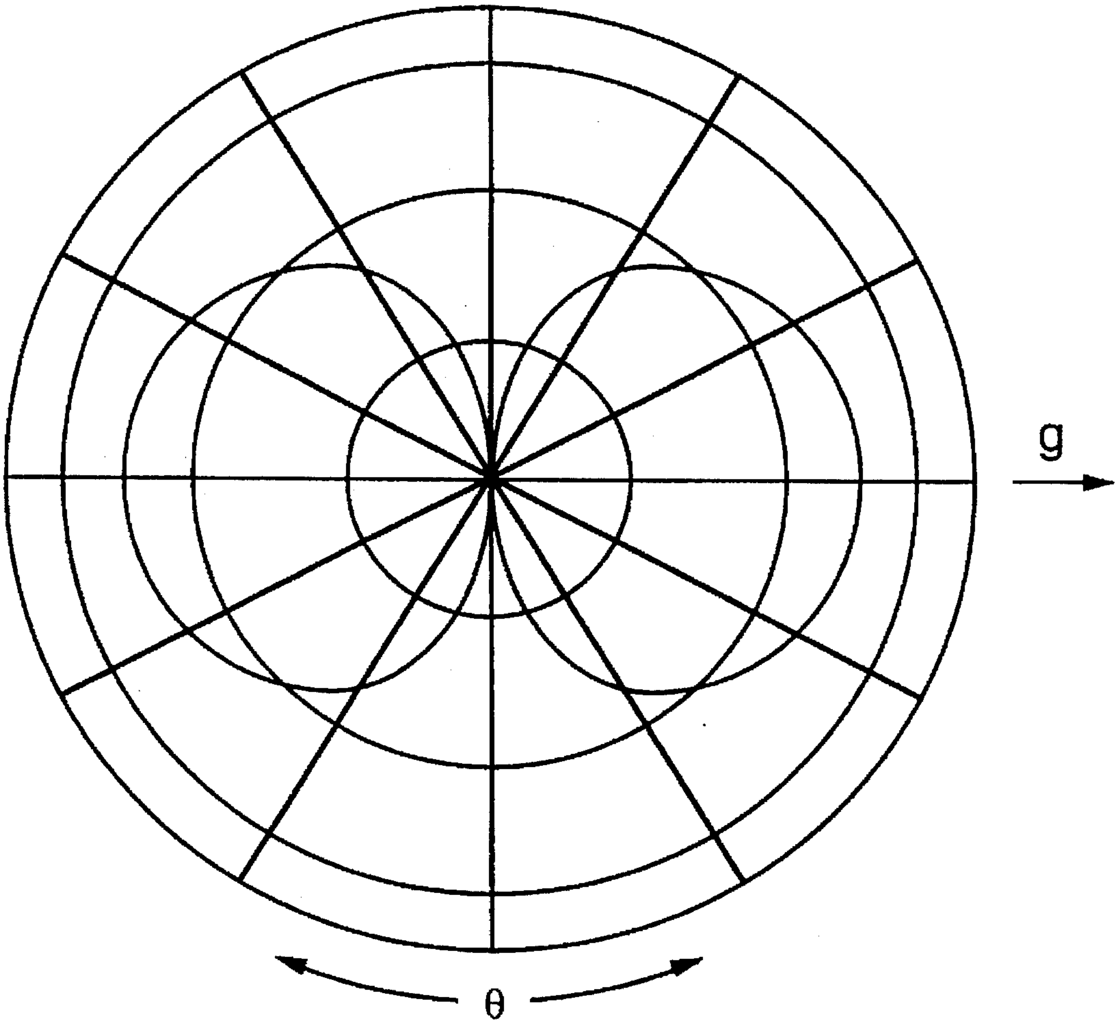

FIG. 51

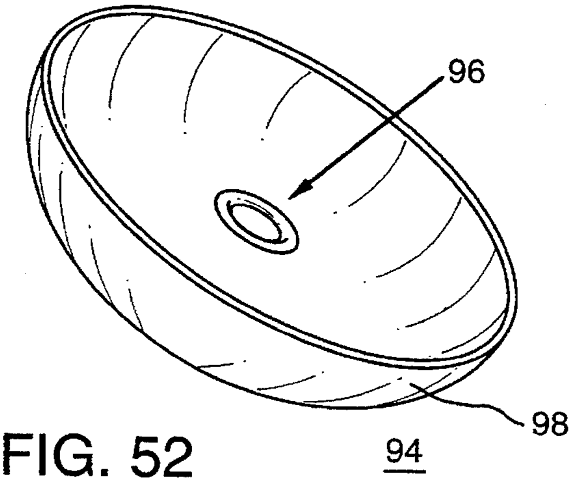

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FIG. 52

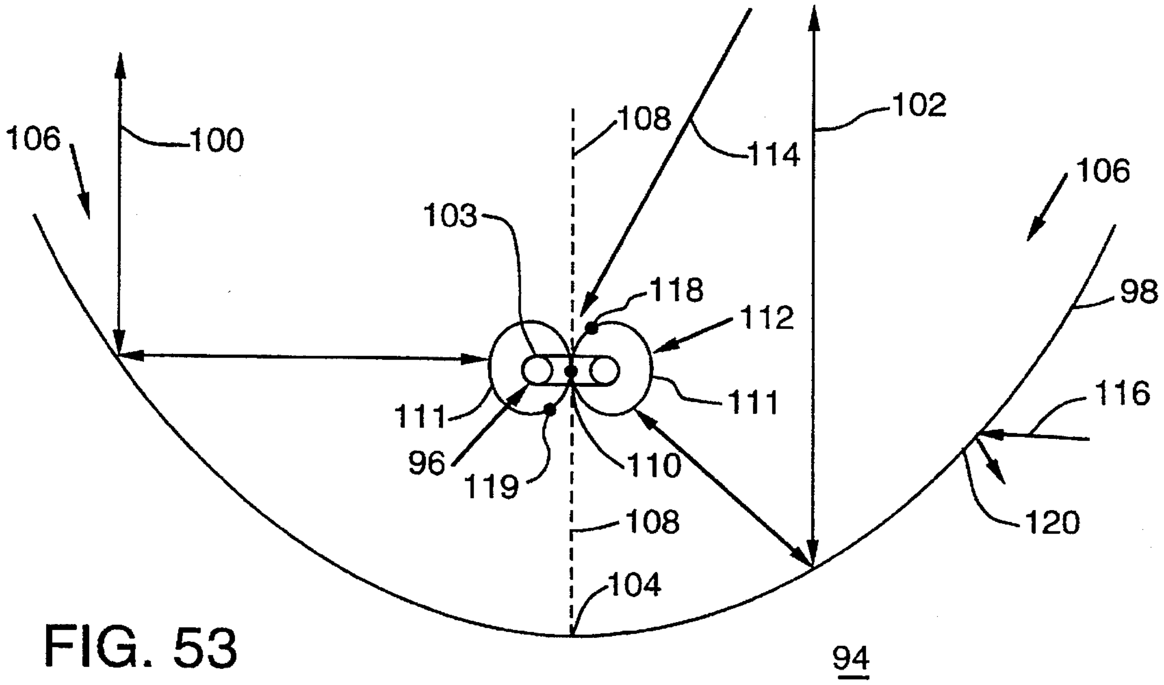

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FIG. 53

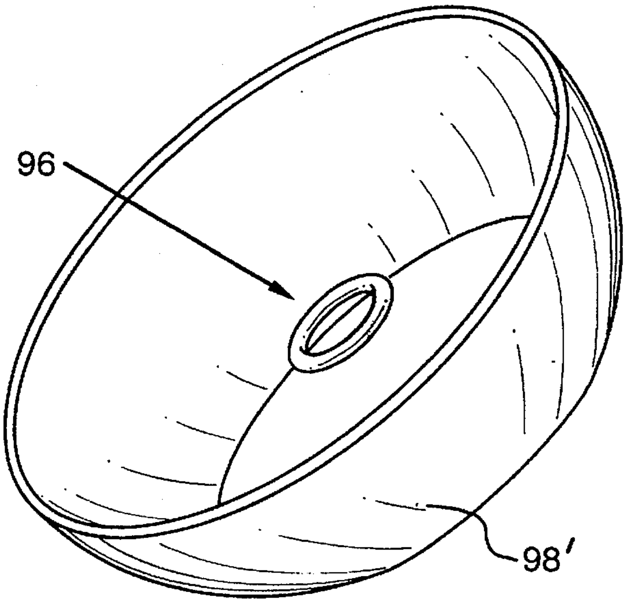
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FIG. 54

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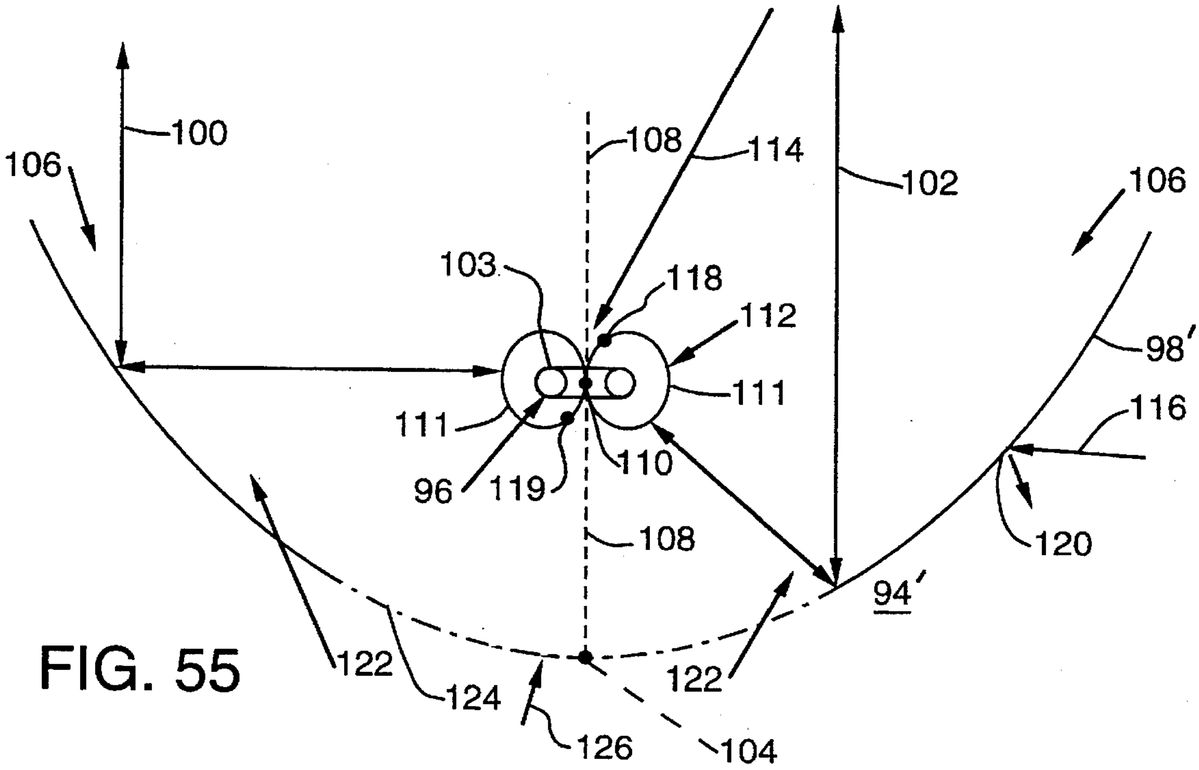
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FIG. 55

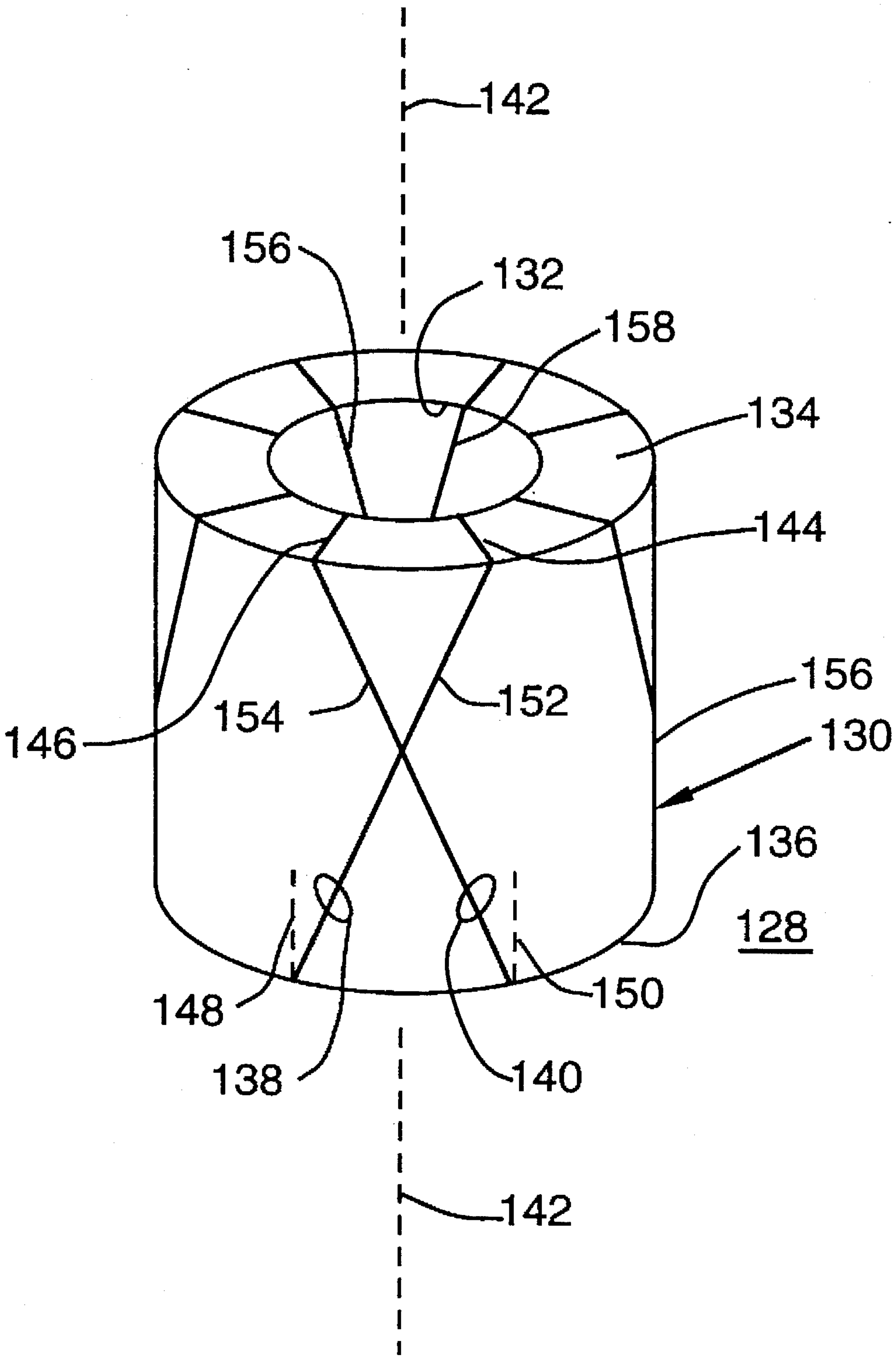
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FIG. 56

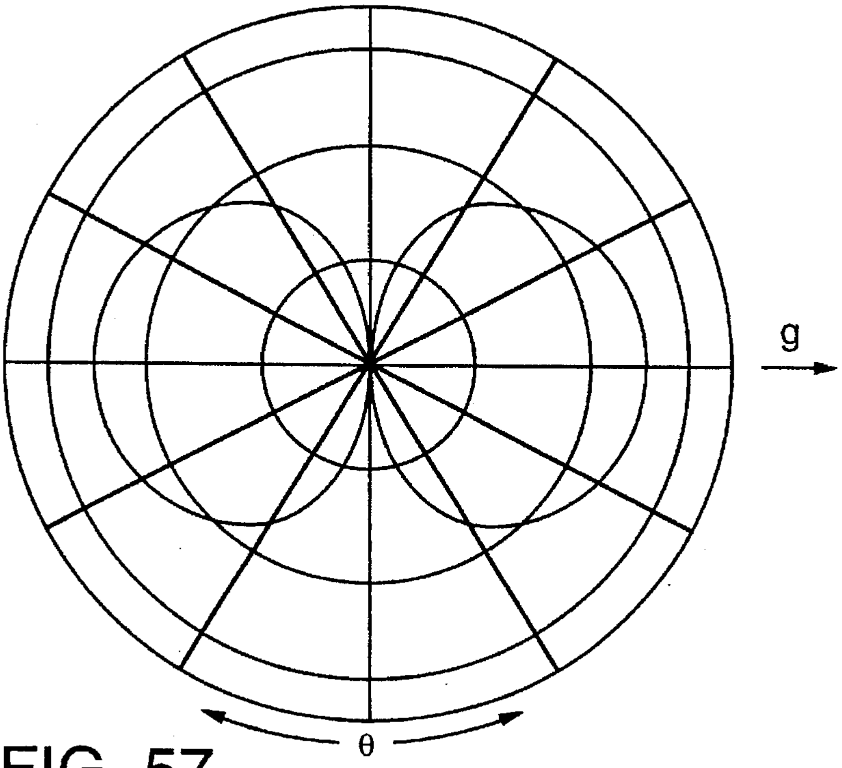

FIG. 57

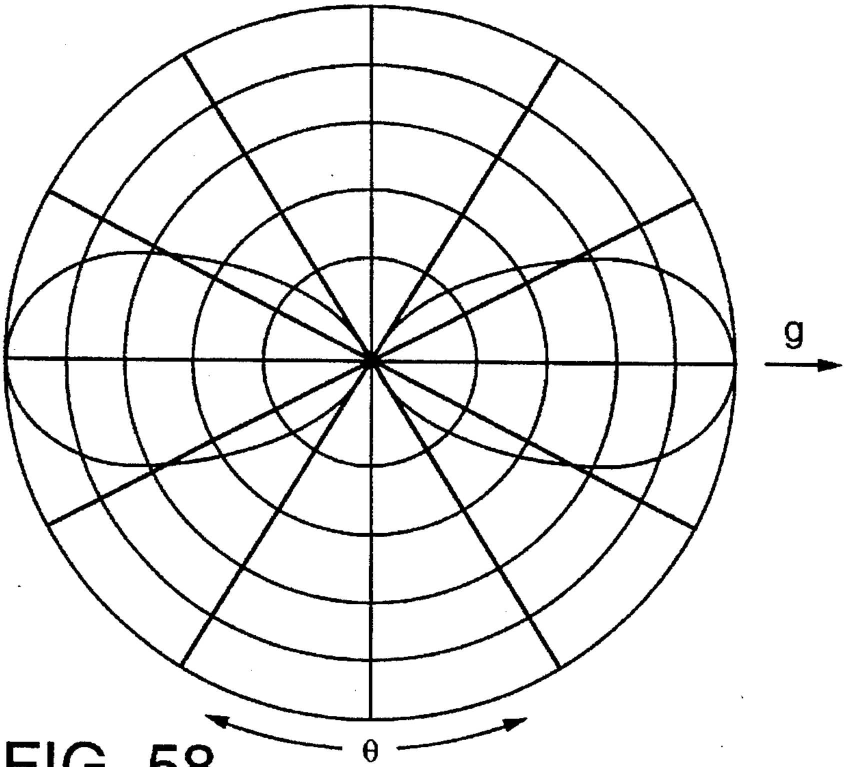

FIG. 58

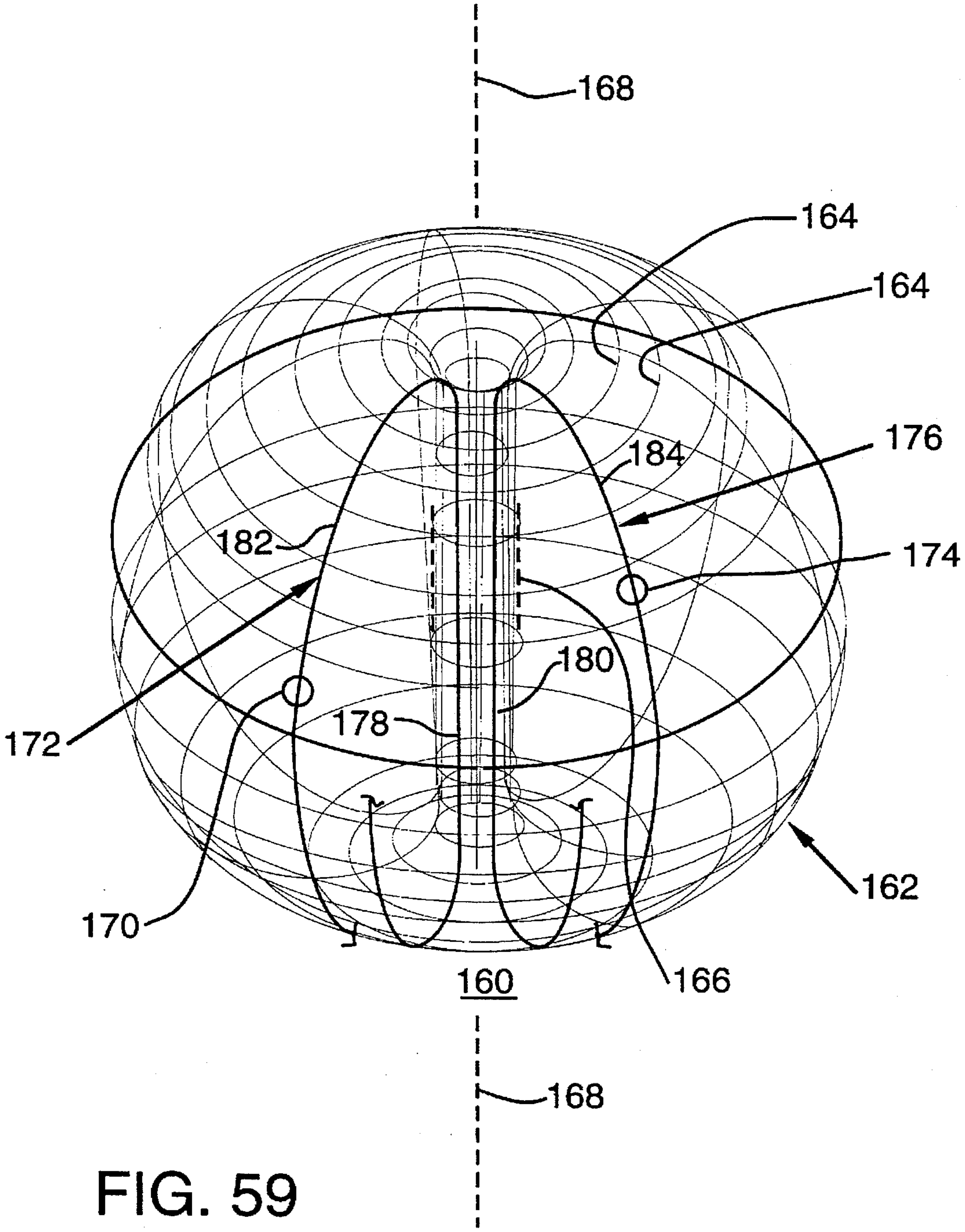

FIG. 59

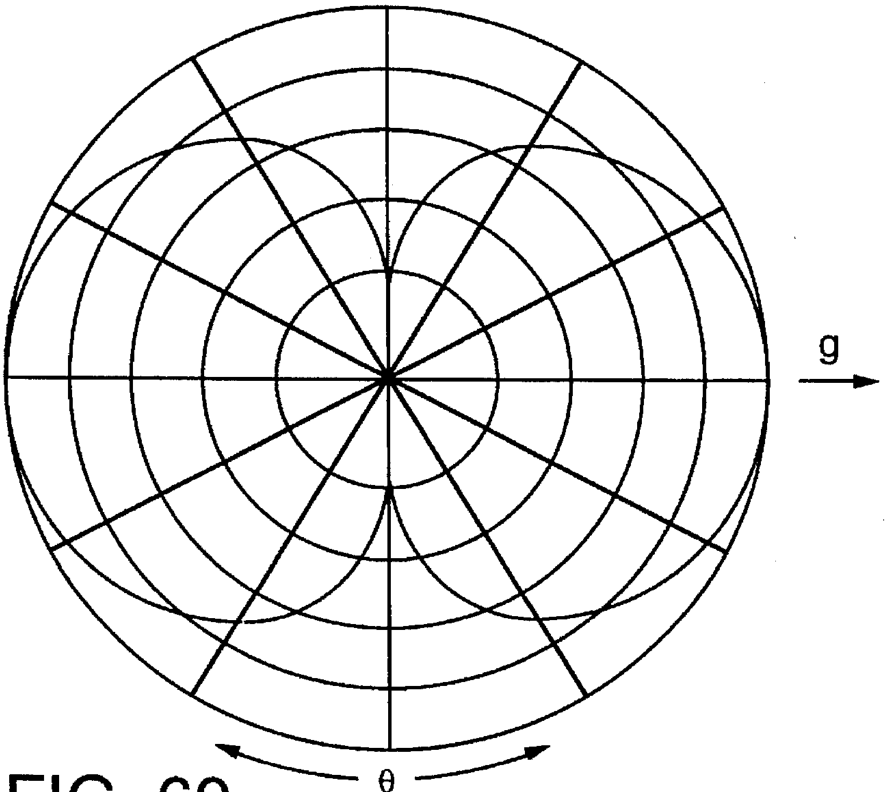

FIG. 60

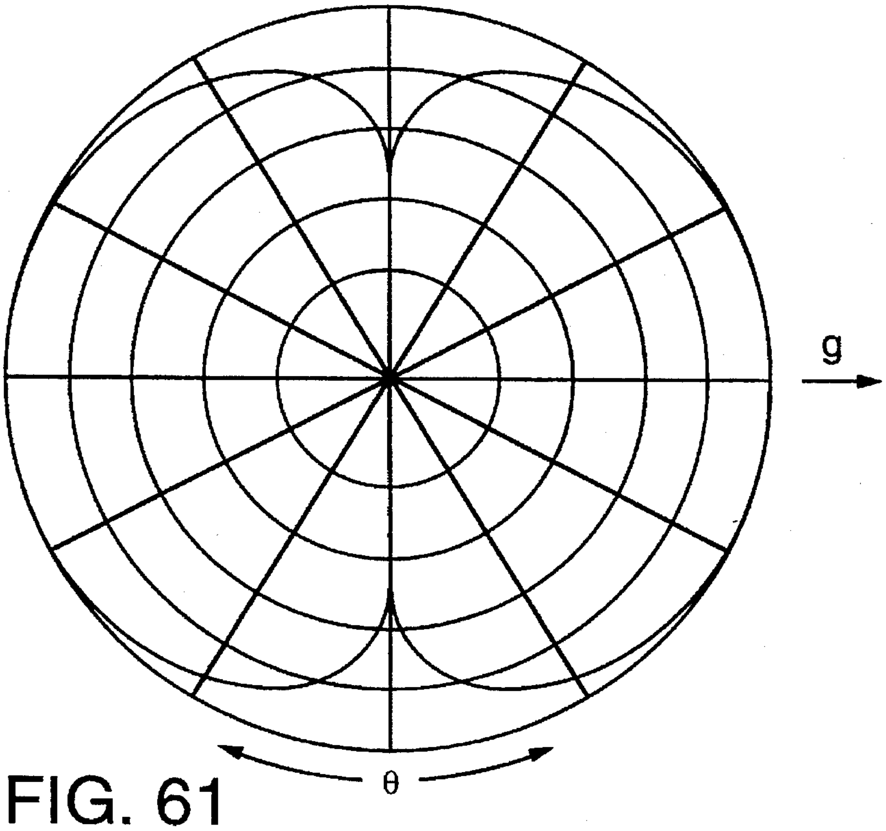

FIG. 61

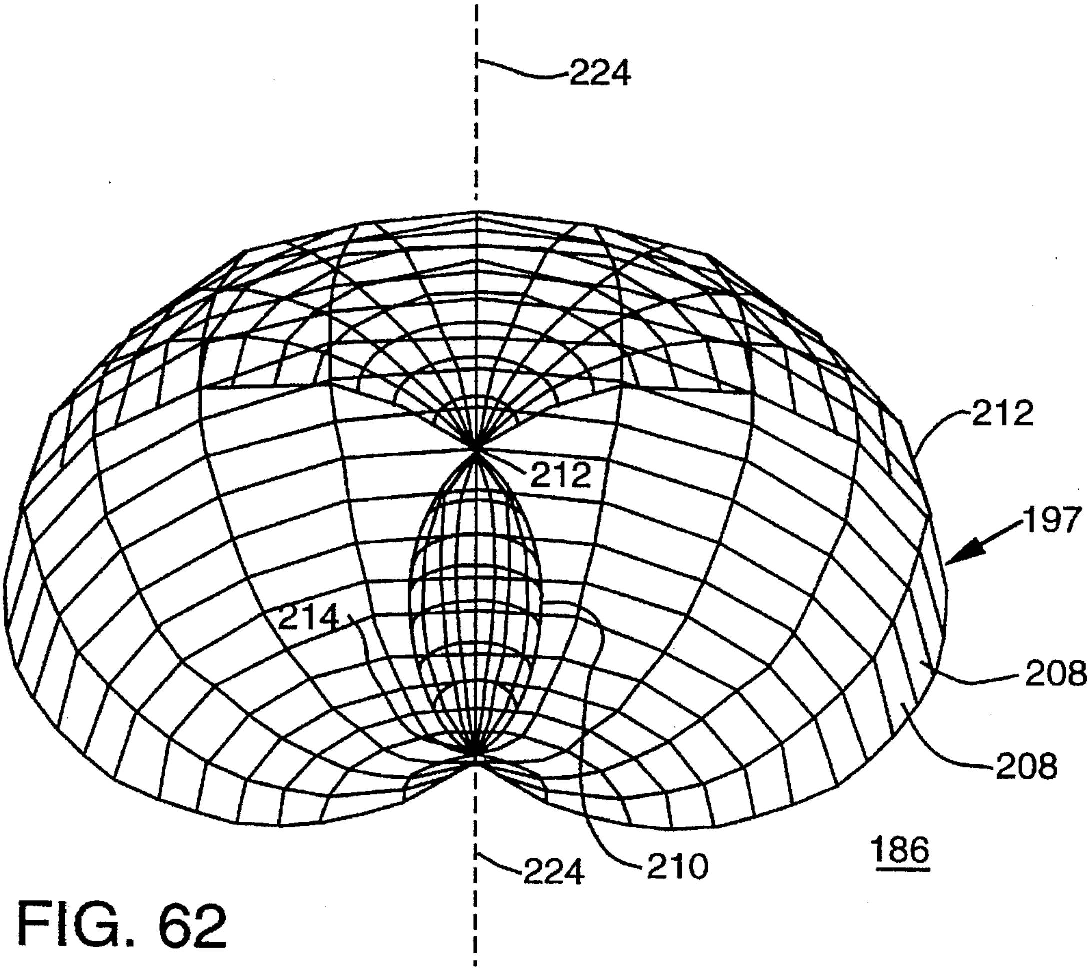
224
212
212
197
214
208
208
224
210
186

FIG. 62

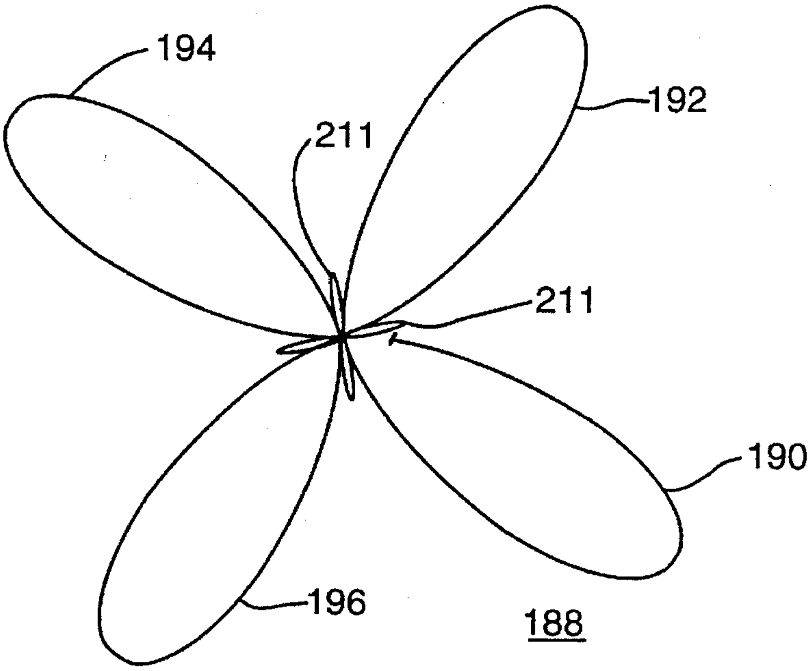
194
192
211
211
190
196
188

FIG. 63

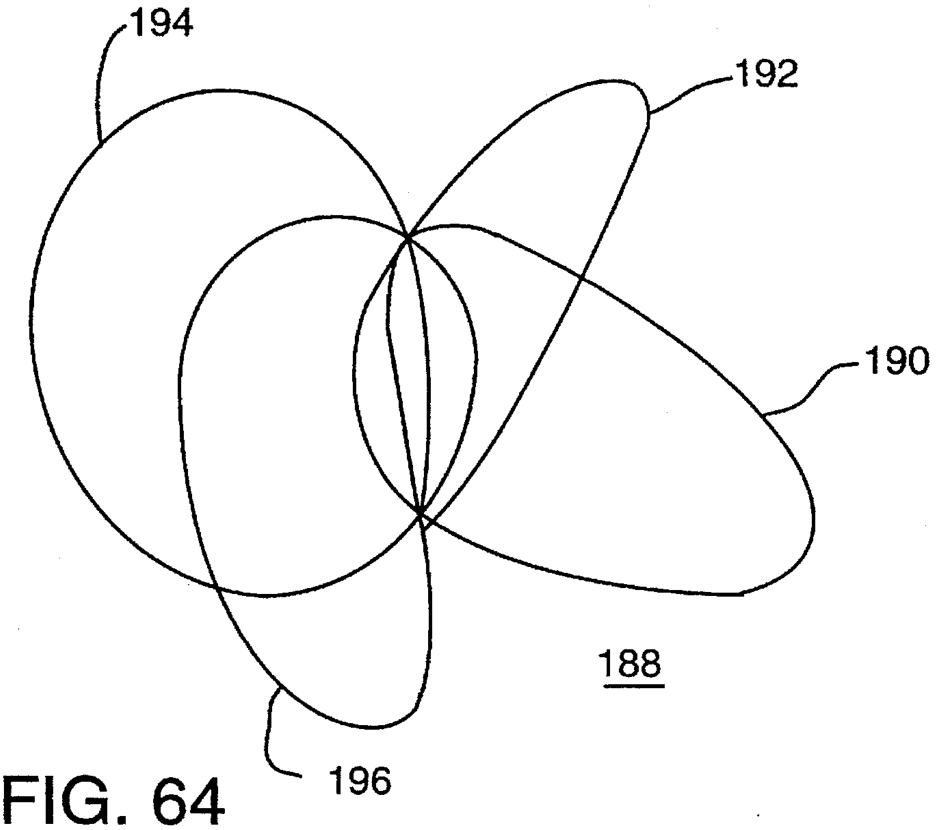
194
192
190
188
196

FIG. 64

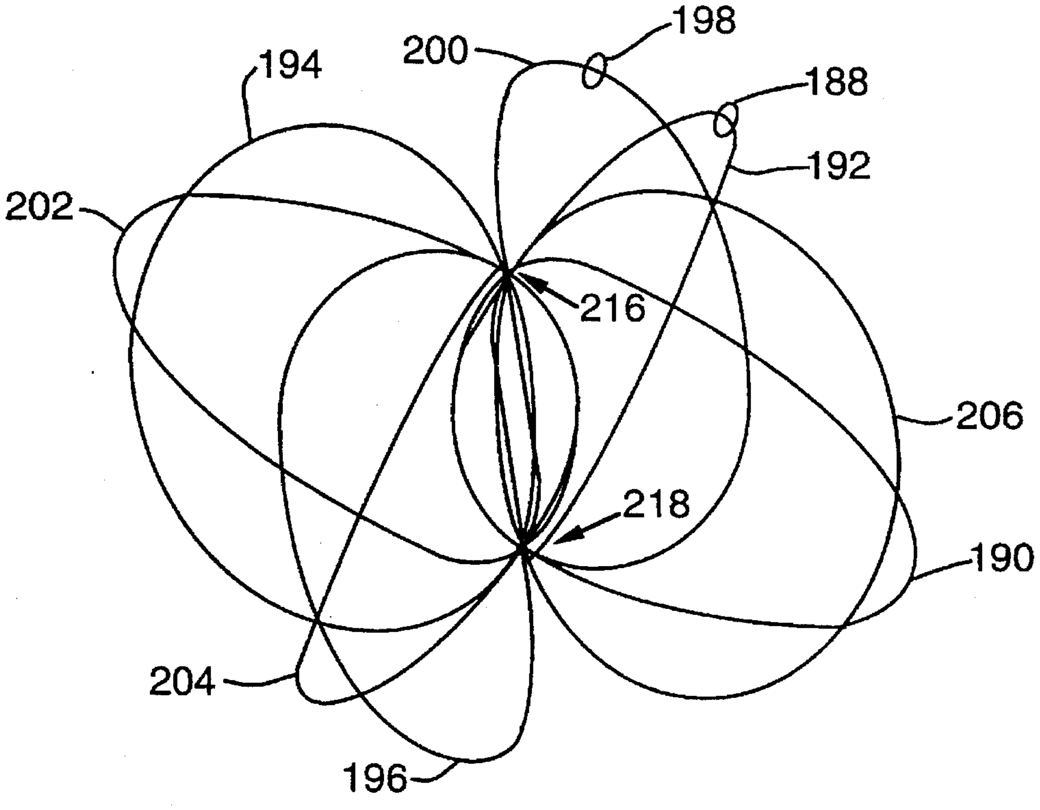
198
200
194
188
192
202
216
206
218
190
204
196

FIG. 65

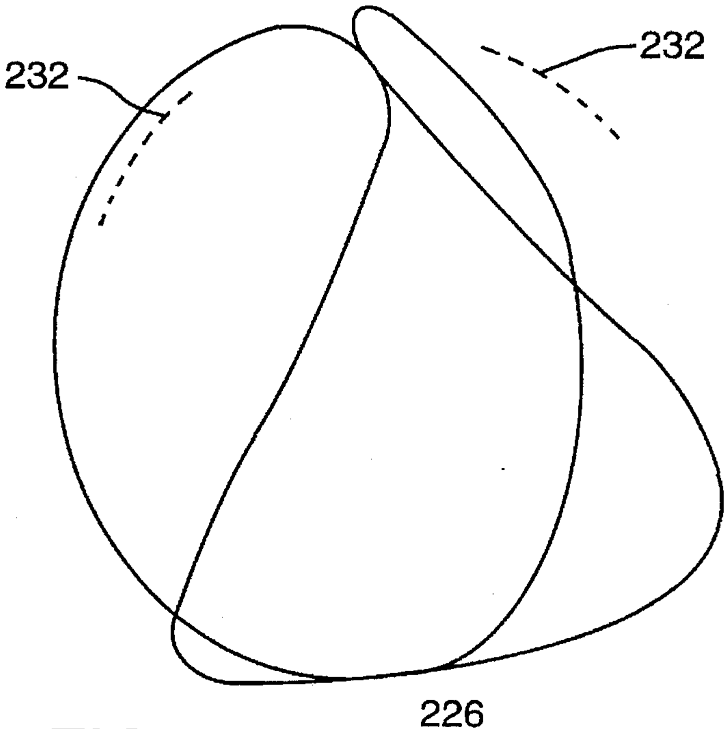

FIG. 66

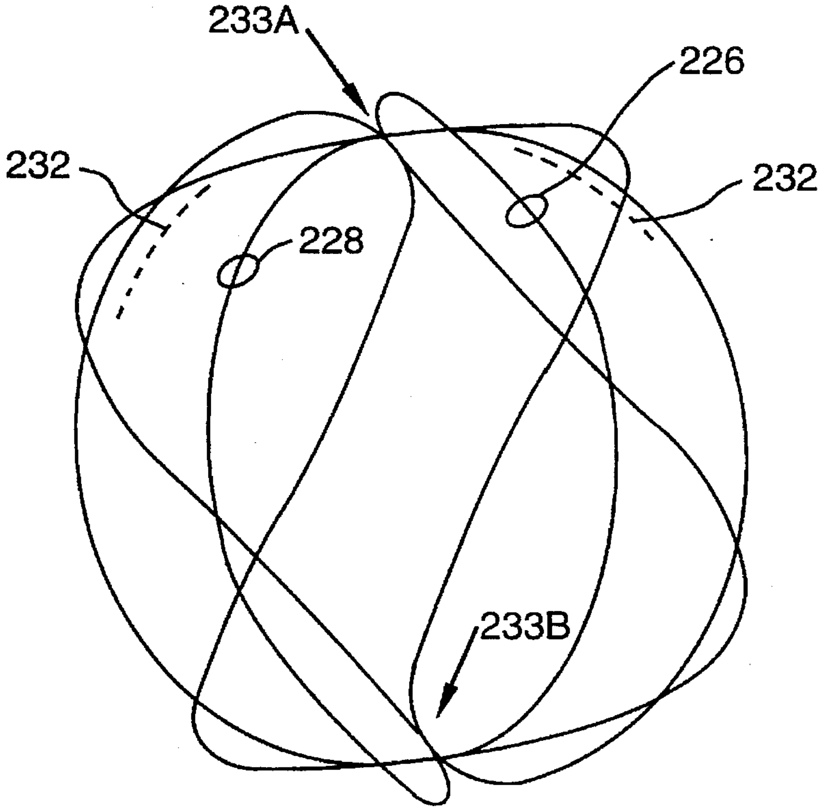

FIG. 67

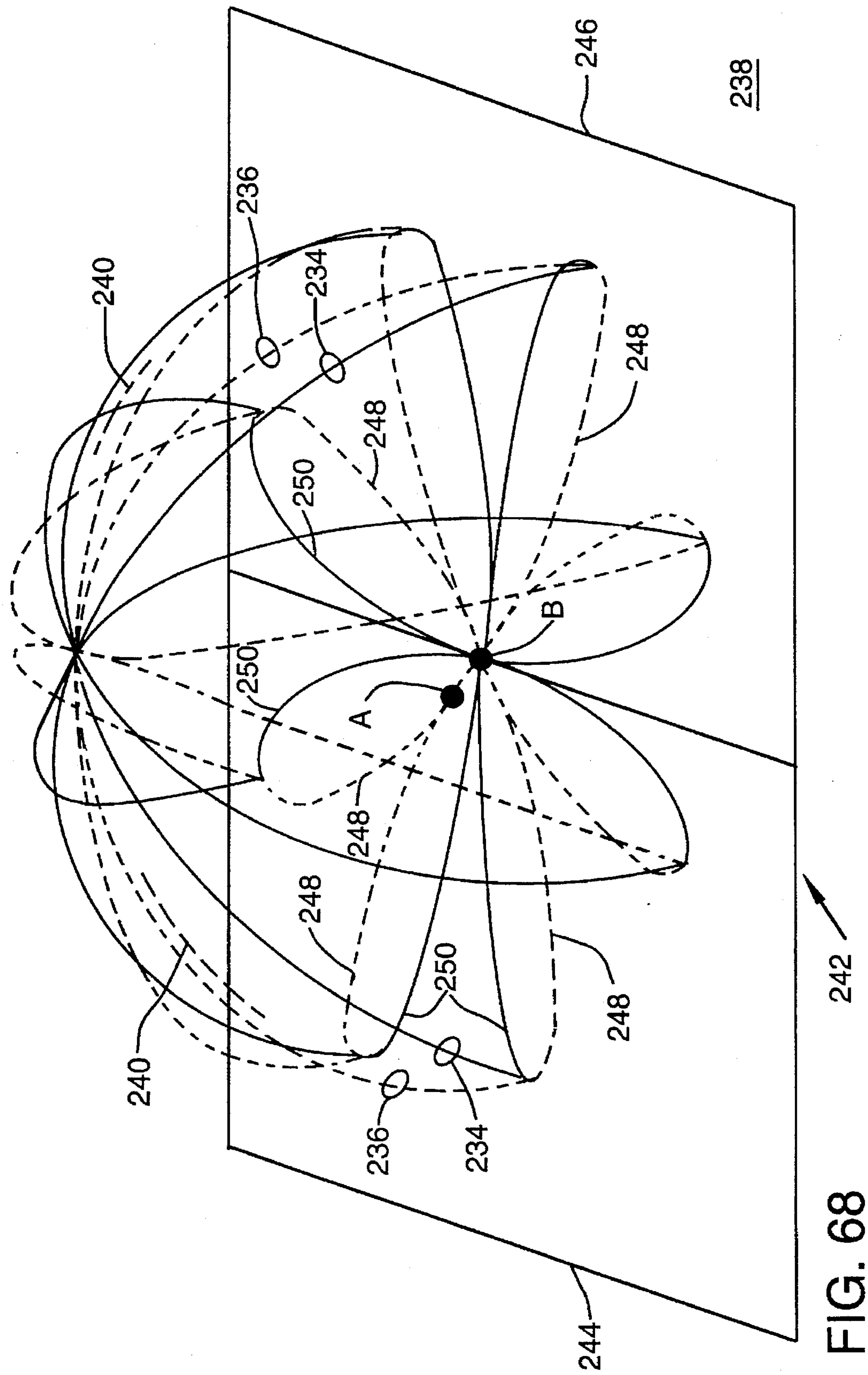
238
246
236
234
240
248
248
250
B
250
A
248
248
250
248
242
240
236
234
244

FIG. 68

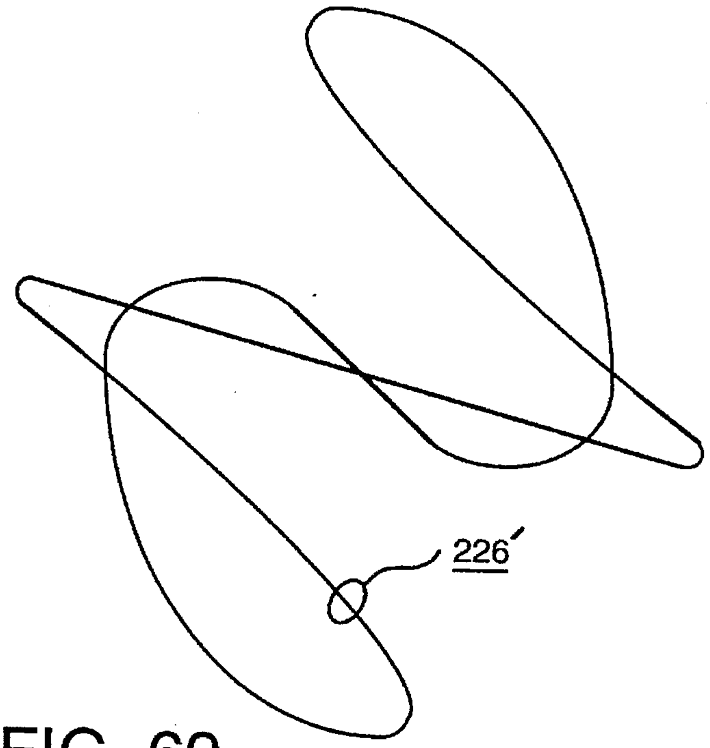

FIG. 69

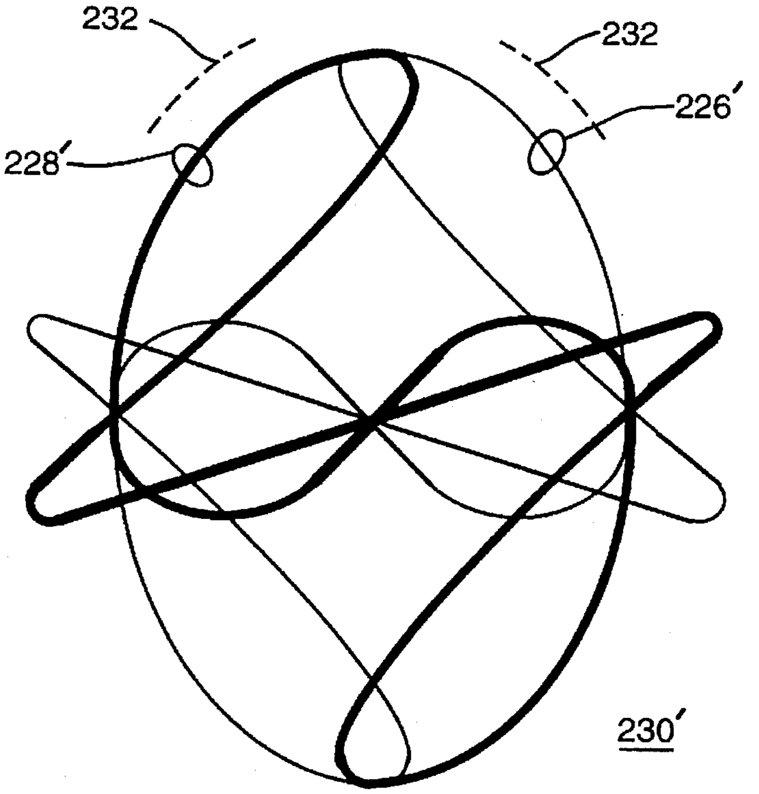

FIG. 70

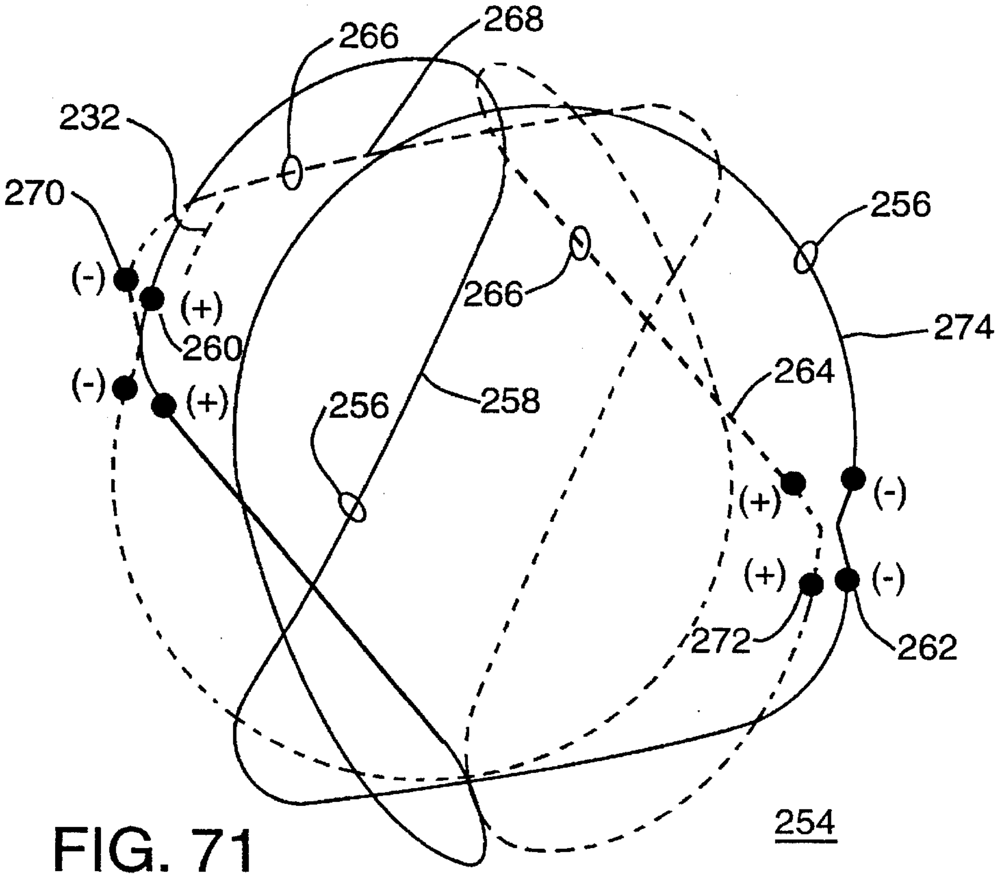
266
268
232
270
(-)
(+)
260
(-)
(+)
266
256
258
256
274
264
(+)
(-)
(+)
(-)
272
262
254

FIG. 71

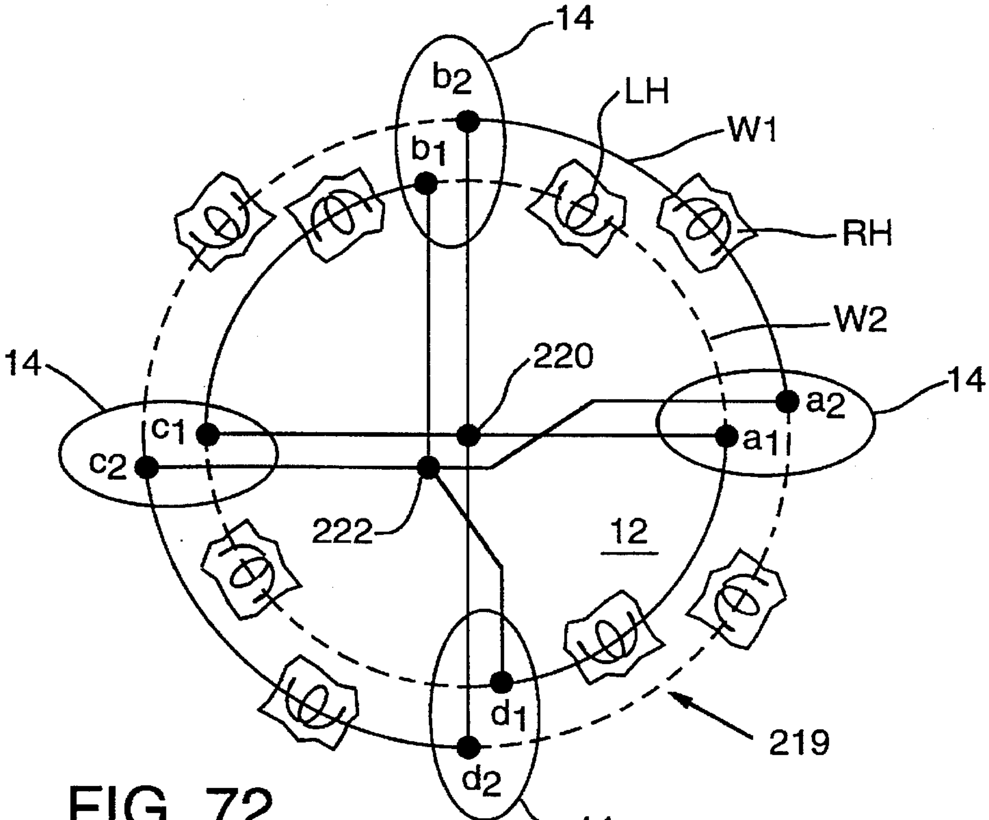
14
b2
LH
W1
b1
RH
W2
220
14
14
c1
a2
c2
a1
222
12
d1
219
d2
14

FIG. 72

CONTRAWOUND ANTENNA

This is a continuation-in-part of application Ser. No. 07/992,970, filed Dec. 15, 1992, now U.S. Pat. No. 5,442,369.

TECHNICAL FIELD

This invention relates to transmitting and receiving antennas, and in particular, helically wound antennas.

BACKGROUND OF THE INVENTION

Antenna efficiency at a frequency of excitation is directly related to the effective electrical length, which is related to the signal propagation rate by the well known equation using the speed of light C in free space, wavelength λ, and frequency f:

$$\lambda = C/f$$

As is known, antenna electrical length should be one wavelength, one half wavelength (a dipole) or one quarter wavelength with a ground plane to minimize all but real antenna impedances. When these characteristics are not met, antenna impedance changes creating standing waves on the antenna and antenna feed (transmission line), increasing the standing wave ratio all producing energy loss and lower radiated energy.

A typical vertical whip antenna (a monopole) possesses an omnidirectional vertically polarized pattern, and such an antenna can be comparatively small at high frequencies, such as UHF. However, at lower frequencies the size becomes problematic, leading to the very long lines and towers used in the LF and MF bands. The long range transmission qualities in the lower frequency bands are advantageous but the antenna, especially a directional array can be too large to have a compact portable transmitter. Even at high frequencies, it may be advantageous to have a physically smaller antenna with the same efficiency and performance as a conventional monopole or dipole antenna.

Over the years different techniques have been tried to create compact antennas with directional characteristics, especially vertical polarization, which has been found to be more efficient (longer range) than horizontal polarization, the reason being the horizontally polarized antennae sustain more ground wave losses.

In terms of directional characteristics, it is recognized that with certain antenna configurations it is possible to negate the magnetic field produced in the antenna in a particular polarization and at the same time increase the electric field, which is normal to the magnetic field. Similarly, it is possible to negate the electric field and at the same time increase the magnetic field.

The equivalence principle is a well known concept in the field of electromagnetic arts stating that two sources producing the same field inside a given region are said to be equivalent, and that equivalence can be shown between electric current sources and corresponding magnetic current sources. This is explained in Section 3–5 of the 1961 reference *Time Harmonic Electromagnetic Fields* by R. F. Harrington. For the case of a linear dipole antenna element which carries linear electric currents, the equivalent magnetic source is given by a circular azimuthal ring of magnetic current. A solenoid of electric current is one obvious way to create a linear magnetic current. A solenoid of electric current disposed on a toroidal surface is one way of creating the necessary circular azimuthal ring of magnetic current.

The toroidal helical antenna consists of a helical conductor wound on a toroidal form and offers the characteristics of radiating electromagnetic energy in a pattern that is similar to the pattern of an electric dipole antenna with an axis that is normal to the plane of and concentric with the center of the toroidal form. The effective transmission line impedance of the helical conductor retards, relative to free space propagation rate, the propagation of waves from the conductor feed point around the helical structure. The reduced velocity and circular current in the structure makes it possible to construct a toroidal antenna as much as an order of magnitude or more smaller that the size of a corresponding remnant dipole (linear antenna). The toroidal design has low aspect ratio, since the toroidal helical design is physically smaller than the simple resonant dipole structure, but with similar electrical radiation properties. A simple single-phase feed configuration will give a radiation pattern comparable to a ½ wavelength dipole, but in a much smaller package.

In that context, U.S. Pat. Nos. 4,622,558 and 4,751,515 discusses certain aspects of toroidal antennas as a technique for creating a compact antenna by replacing the conventional linear antenna with a self resonant structure that produces vertically polarized radiation that will propagate with lower losses when propagating over the earth. For low frequencies, serf-resonant vertical linear antennas are not practical, as noted previously, and the self-resonant structure explained in these patents goes some way to alleviating the problem of a physically unwieldy and electrically inefficient vertical elements at low frequencies.

The aforementioned patents initially discuss a monofilar toroidal helix as a building block for more complex directional antennas. Those antennas may include multiple conducting paths fed with signals whose relative phase is controlled either with external passive circuits or due to specific self resonant characteristics. In a general sense, the patents discuss the use of so called contrawound toroidal windings to provide vertical polarization. The contrawound toroidal windings discussed in these patents are of an unusual design, having only two terminals, as described in the reference Birdsall, C. K., and Everhart, T. E., "Modified Contra-Wound Helix Circuits for High-Power Traveling Wave Tubes", *IRE Transactions on Electron Devices*, October, 1956, p. 190. The patents point out that the distinctions between the magnetic and electric fields/currents and extrapolates that physically superimposing two monofilar circuits which are contrawound with respect to one another on a toroid a vertically polarized antenna can be created using a two port signal input. The basis for the design is the linear helix, the design equations for which were originally developed by Kandoian & Sichak in 1953 (mentioned the U.S. Pat. No. 4,622,558).

The prior art, such as the aforementioned patents, speaks in terms of elementary toroidal embodiments as elementary building blocks to more complex structures, such as two toroidal structures oriented to simulate contrawound structures. For instance, the aforementioned patent discusses a torus (complex or simple) that is intended to have an integral number of guided wavelengths around the circumference of the circle defined by the minor axis of the torus.

A simple toroidal antenna, one with a monofilar design, responds to both the electric and magnetic field components of the incoming (received) or outputed (transmitted) signals. On the other hand, muitifilar (multiwinding) may have the same pitch sense or different pitch sense in separate windings on separate toroids, allowing providing antenna directionality and control of polarization. One form of helix is in the form of a ring and bridge design, which exhibits some but not all of the qualities of a basic contrawound winding configuration.

As is known, a linear solenoidal coil creates a linear magnetic field along its central axis. The direction of the magnetic field is in accordance with the "right hand rule", whereby if the fingers of a right hand are curled inward towards the palm and pointed in the direction of the circular current flow in the solenoid, then the direction of the magnetic field is the same as that of the thumb when extended parallel to the axis about which the fingers are curled. (See e.g. **FIG. 47**, infra.) When this rule is applied for solenoid coils wound in a right-hand sense, as in a right-hand screw thread, both the electric current and the resulting magnetic field point in the same direction, but a coil in a left-hand sense, has the electric current and resulting magnetic field point in opposite directions. The magnetic field created by the solenoidal coil is sometimes termed a magnetic current. By combining a right-hand and left-hand coil on the same axis to create a contra-wound coil and feeding the individual coil elements with oppositely directed currents, the net electric current is effectively reduced to zero, while the net magnetic field is doubled from that of the single coil alone.

As is also known, a balanced electrical transmission line fed by a sinusoidal AC source and terminated with a load impedance propagates waves of currents from the source to the load. The waves reflect at the load and propagate back towards the source, and the net current distribution on the transmission line is found from the sum of the incident and reflected wave components and can be characterized as standing waves on the transmission line. (See e.g. **FIG. 13**, infra.) With a balanced transmission line, the current components in each conductor at any given point along the line are equal in magnitude but opposite in polarity, which is equivalent to the simultaneous propagation of oppositely polarized by equal magnitude waves along the separate conductors. Along a given conductor, the propagation of a positive current in one direction is equivalent to the propagation of a negative current in the opposite direction. The relative phase of the incident and reflected waves depends upon the impedance of the load element, Z_L. For I_0=incident current signal and I_a=to reflected current signal, with reference to **FIG. 13**, infra. then the reflection coefficient ρi is defined as:

$$\rho_i = \frac{I_1}{I_0} = \frac{-I_1'}{I_0} = \frac{\frac{Z_L}{Z_0} - 1}{\frac{Z_L}{Z_0} + 1}$$

Since the incident and reflected currents travel in opposite directions, the equivalent reflected current, $I_1' = -I_1$ gives the magnitude of the reflected current with respect to the direction of the incident current I_0.

DISCLOSURE OF THE INVENTION

An object of the present invention is to provide a compact vertically polarized antenna, especially suited to low frequency long distance wave applications, but useful at any frequency where a physically low profile or inconspicuous antenna package is desirable.

It is a still further object of the present invention to provide a directional antenna suitable for use of a motor vehicle or ship.

It is yet a further object of the present invention to provide an antenna which is approximately omnidirectional in all directions.

It is another further object of the present invention to provide an antenna having a maximum radiation gain in directions normal to the direction of polarization and a minimum radiation gain in the direction of polarization.

It is still another further object of the present invention to provide an antenna having a simplified feed configuration that is readily matched to a radio frequency (RF) power source.

It is yet another further object of the present invention to provide an antenna which enhances radial energy radiation.

It is yet a still further object of the present invention to provide an antenna which enhances vertical energy radiation.

According to the present invention a toroidal antenna has a toroidal surface and first and second windings that comprise insulated conductors each extending as a single closed circuit around the surface in segmented helical pattern. The toroid has an even number of segments, e.g. four segments, but generally greater than or equal to two segments. Each part of one of the continuous conductors within a given segment is contrawound with respect to that part of the same conductor in the adjacent segments. Adjacent segments of the same conductor meet at nodes or junctions (winding reversal points). Each of the two continuous conductors are contrawound with respect to each other within every segment of the toroid. A pair of nodes (a port) is located at the boundary between each adjacent pairs of segments. From segment to segment, the polarity of current flow from an unipolar signal source is reversed through connections at the port with respect to the conductors to which the port's nodes are connected. According to the invention, the conductors at the junctions located at every other port are severed and the severed ends are terminated with matched purely reactive impedances which provides for a 90 degree phase shift of the respective reflected current signals. This provides for the simultaneous cancellation of the net electric currents and the production of a quasi-uniform azimuthal magnetic current within the structure creating vertically polarized electromagnetic radiation.

According to the invention, a series of conductive loops are "poloidally" disposed on, and equally spaced about, a surface of revolution such that the major axis of each loop forms a tangent to the minor axis of the surface of revolution. Relative to the major axis of the surface of revolution, the centermost ends of all loops are connected together at one terminal, and the remaining ends of all loops are connected together at a second terminal. A unipolar signal source is applied across the two terminals and since the loops are electrically connected in parallel, the magnetic fields produced by all loops are in phase thus producing a quasi-uniform azimuthal magnetic field, causing vertically polarized omnidirectional radiation.

According to the invention, the number of loops is increased, the conductive elements becoming conductive surface of revolution, which could be either continuous or radially slotted. The operating frequency is lowered by introducing either series inductance or parallel capacitance relative to the composite antenna terminals.

According to the invention, capacitance may be added with the addition of a pair of parallel conductive plates which act as a hub to a conductive surface of revolution. The surface of revolution is slit at the junction with the plates, with one plate being electrically connected to one side of the slit, and a second plate being connected to the other side of the slit. The conductive surface of revolution may be further slitted radially to emulate a series of elementary loop antennas. The bandwidth of the structure may be increased if the radius and shape of the surface of revolution are varied with the corresponding angle of revolution.

According to the invention, an electromagnetic antenna includes a multiply connected surface; a first insulated conductor means extending in a first generally helical conductive path around and at least partially over the multiply connected surface with at least a first helical pitch sense; a second insulated conductor means extending in a second generally helical conductive path around and at least partially over the multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the multiply connected surface; first and second signal terminals respectively electrically connected to the first and second insulated conductor means; and reflector means for directing the antenna signal with respect to the multiply connected surface for reception or transmission of the antenna signal.

According to the invention, an electromagnetic antenna includes a multiply connected surface having a major axis; a first insulated conductor means extending in a first partially helical conductive path around and at least partially over the muitiply connected surface with at least a first helical pitch sense; a second insulated conductor means extending in a second partially helical conductive path around and at least partially over the multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the multiply connected surface, with the first and second partially helical conductive paths, when generally perpendicular to the major axis of the multiply connected surface, being generally radial with respect to the major axis of the multiply connected surface, and otherwise being generally helically oriented; and first and second signal terminals respectively electrically connected to the first and second insulated conductor means.

According to the invention, an electromagnetic antenna includes a generally spherical surface having a conduit along a major axis thereof; a first insulated conductor means extending in a first partially helical conductive path around and at least partially over the generally spherical surface with at least a first helical pitch sense; a second insulated conductor means extending in a second partially helical conductive path around and at least partially over the generally spherical surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the generally spherical surface, with the first and second partially helical conductive paths passing through the conduit of the generally spherical surface and being generally parallel to the major axis thereof within the conduit, and otherwise being generally helically oriented; and first and second signal terminals respectively electrically connected to the first and second insulated conductor means.

According to the invention, an electromagnetic antenna includes a multiply connected surface having a major radius which is greater than zero and a minor radius which is greater than the major radius; a first insulated conductor means extending in a first generally helical conductive path around and at least partially over the multiply connected surface with at least a first helical pitch sense; a second insulated conductor means extending in a second generally helical conductive path around and at least partially over the multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the multiply connected surface; and first and second signal terminals respectively electrically connected to the first and second insulated conductor means.

According to the invention, an electromagnetic antenna includes a spherical surface; a first insulated conductor means extending in a first conductive path around and at least partially over the spherical surface with at least a first winding sense; a second insulated conductor means extending in a second conductive path around and at least partially over the spherical surface with at least a second winding sense, which is opposite from the first winding sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the spherical surface; and first and second signal terminals respectively electrically connected to the first and second insulated conductor means.

According to the invention, an electromagnetic antenna includes a hemispherical surface; a first insulated conductor means extending in a first conductive path around and at least partially over the hemispherical surface with at least a first winding sense; a second insulated conductor means extending in a second conductive path around and at least partially over the hemispherical surface with at least a second winding sense, which is opposite from the first winding sense, in order that the first and second insulated conductor means are contrawound relative to each other around and at least partially over the hemispherical surface; and first and second signal terminals respectively electrically connected to the first and second insulated conductor means.

The invention provides a compact, vertically polarized antenna with greater gain for a wider frequency spectrum as compared to a bridge and ring configuration. Other objects, benefits and features of the invention will be apparent to one skilled in the art.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a schematic of a four segment helical antenna according to the invention.

FIG. **2** is an enlarged view of windings in FIG. **1**.

FIG. **3** is an enlarged view of whigs in an alternative embodiment of the invention.

FIG. **4** is a schematic of a two segment (two part) helical antenna embodying the invention.

FIG. **5** is two port helical antenna with variable impedances at winding reversal points in an alternate embodiment and for antenna tuning according to the invention.

FIG. **6** is a field plot showing the field pattern for the antenna shown in FIG. **1**.

FIGS. **7**, **8** and **9** are current and magnetic field plots relative to toroidal node positions for the antenna shown in FIG. **1**.

FIGS. **10**, **11** and **12** are current and magnetic field plots relative to toroidal positions between nodes for the antenna shown in FIG. **4**.

FIG. **13** is an equivalent circuit for a terminated transmission line.

FIG. **14** is an enlarged view of poloidal windings on a toroid according to the present invention for tuning capability, improved electric field cancellation and simplified construction.

FIG. **15** is a simplified block diagram of a four quadrant version of an antenna embodying the present invention with impedance and phase matching elements.

FIG. **16** is an enlargement of the windings of an antenna embodying the invention with primary and secondary impedance matching coils connecting the windings.

FIG. **17** is an equivalent circuit for an antenna embodying the invention illustrating a means of tuning.

FIGS. **18** and **19** are schematics of a portion of a toroidal antenna using dosed metal foil tuning elements around the toroid for purposes of tuning as in FIG. **17**.

FIG. **20** is a schematic showing an antenna embodying the present invention using a tuning capacitor between opposed nodes.

FIG. **21** is an equivalent circuit of an alternate tuning method for of a quadrant antenna embodying the present invention.

FIG. **22** shows an antenna according to the present invention with a conductive foil wrapper on the toroid for purposes of tuning as in FIG. **21**.

FIG. **23** is a section along line **23—23** in FIG. **24**.

FIG. **24** is a perspective view of a foil covered antenna according to the present invention.

FIG. **25** shows an alternate embodiment of an antenna with "rotational symmetry" embodying the present invention.

FIG. **26** is a functional block diagram of an FM transmitter using a modulator controlled parametric tuning device on an antenna.

FIG. **27** shows an omnidirectional poloidal loop antenna.

FIG. **28** is a side view of one loop in the antenna shown in FIG. **27**.

FIG. **29** is an equivalent circuit for the loop antenna.

FIG. **30** is a side view of a square loop antenna.

FIG. **31** is a partial cutaway view of cylindrical loop antenna according to the invention.

FIG. **32** is a section along **32—32** in FIG. **31** and includes a diagram of the current in the windings.

FIG. **33** is a partial view of a toroid with toroid slots for tuning and for emulation of a poloidal loop configuration according to the present invention.

FIG. **34** shows a toroidal antenna with a toroid core tuning circuit.

FIG. **35** is an equivalent circuit for the antenna shown in FIG. **34**.

FIG. **36** is a cutaway of a toroidal antenna with a central capacitance tuning arrangement according to the present invention.

FIG. **37** is a cutaway of an alternate embodiment of the antenna shown in FIG. **36** with poloidal windings.

FIG. **38** is an alternate embodiment with variable capacitance tuning.

FIG. **39** is a plan view of a square toroidal antenna according to the present invention for augmenting antenna bandwidth and with slots for tuning or for emulation of a poloidal loop configuration.

FIG. **40** is a section along **40—40** in FIG. **39**.

FIG. **41** is a plan view of an alternate embodiment of the antenna shown in FIG. **39** having six sides with slots for tuning or for emulation of a poloidal configuration.

FIG. **42** is a section along **42—42** in FIG. **41**.

FIG. **43** is a conventional linear helix.

FIG. **44** is an approximate linear helix.

FIG. **45** is a composite equivalent of the configuration shown in FIG. **45** assuming that the magnetic field is uniform or quasi uniform over the length of the helix.

FIG. **46** shows a contrawound toroidal helical antenna with an external loop and a phase shift and proportional control.

FIG. **47** shows fight hand sense and left hand sense equivalent circuits and associated electric and magnetic fields.

FIG. **48** is a schematic of a series fed antenna.

FIG. **49** is a schematic of another series fed antenna.

FIG. **50** is a schematic of another antenna having one or two feed ports.

FIG. **51** is a representative elevation radiation pattern for toroidal embodiments of the antennas of FIGS. **48–51**.

FIG. **52** is an perspective view of a toroidal antenna with a parabolic reflector.

FIG. **53** is a vertical sectional view of the toroidal antenna of FIG. **52**.

FIG. **54** is an perspective view of a toroidal antenna with an alternative parabolic reflector.

FIG. **55** is a vertical sectional view of the toroidal antenna of FIG. **54**.

FIG. **56** is an isometric view of a cylindrical antenna having contrawound conductors with partially helical and partially radial conductive paths.

FIG. **57** is a representative elevation radiation pattern for a toroidal antenna having helical conductive paths.

FIG. **58** is a representative elevation radiation pattern for the antenna of FIG. **56**.

FIG. **59** is an perspective view of a generally spherical toroid form having a generally circular cross section and a central conduit.

FIG. **60** is a representative elevation radiation pattern for a toroidal antenna having helical conductive paths.

FIG. **61** is a representative elevation radiation pattern for the antenna of FIG. **59**.

FIG. **62** is a vertical sectional perspective view of a toroid form having a minor radius greater than a major radius.

FIG. **63** is a plan view of a conductor with a helical conductive path for the toroid form of FIG. **62**.

FIG. **64** is an perspective view of the conductor of FIG. **63**.

FIG. **65** is an perspective view of contrawound conductors with helical conductive paths for the toroid form of FIG. **62**.

FIG. **66** is an perspective view of a single spherical conductor for a spherical form antenna.

FIG. **67** is an perspective view of contrawound spherical conductors for a spherical form antenna.

FIG. **68** is an perspective view of contrawound hemispherical conductors for a hemispherical form antenna.

FIG. **69** is an perspective view of an alternative single spherical conductor for a spherical form antenna.

FIG. **70** is an perspective view of alternative contrawound spherical conductors for a spherical form antenna.

FIG. **71** is an perspective view of contrawound spherical conductors for a spherical form antenna with series or parallel feed-points.

FIG. **72** is a schematic of a four segment helical antenna for use with the toroidal form of FIG. **62**.

BEST MODE FOR CARRYING OUT THE INVENTION

Referring to FIG. **1**, an antenna **10** comprises two electrically insulated closed circuit conductors (windings) W1 and **W2** that extend around a toroid form **TF** through 4 (n=4) equiangular segments **12**. The windings are supplied with an RF electrical signal from two pins **S1** and **S2**. Within each segment, the winding "contrawound", that is the source for winding **W1** may be right hand (RH), as shown by the dark solid lines, and the same for winding **W2** may be left hand (LH) as shown by the broken lines. Each conductor is assumed to have the same number of helical turns around the form, as determined from equations described below. At a junction or node **14** each winding reverses sense (as shown in the cutaway of each). The signal terminals **S1** and **S2** are connected to the two nodes and each pair of such nodes is termed a "port". In this discussion, each pair of nodes at each of four ports is designated **a1** and **a2**, **b1** and **b2**, **c1** and **c2** and **d1** and **d2**. In FIG. **1**, for instance, there are four ports, a, b, c and d. Relative to the minor axis of TF, at a given port the nodes may be in any angular relation to one another and to the torus, but all ports on the structure will bear this same angular relation if the number of alms in each segment is an integer. For example, FIG. **2** shows diametrically opposed nodes, while FIG. **3** shows overlapping nodes. The nodes overlay each other, but from port to port the connections of the corresponding nodes with terminals or pins **S1** and **S2** are reversed as shown, yielding a configuration in which diametrically opposite segments have the same connections in parallel, with each winding having the same sense. The result is that in each segment the currents in the windings are opposed but the direction is reversed along with the winding sense from segment to segment. It is possible to increase or decrease the segments so long as there are an even number of segments, but it should be understood that the nodes bear a relationship to the effective transmission line length for the toroid (taking into account the change in propagation velocity due to the helical winding and operating frequency). By altering the node locations the polarization and directionality of the antenna can be controlled, especially with an external impedance **16**, as shown in FIG. **5**. The four segment configuration shown here, has been found to produce a vertically polarized omnidirectional field pattern having an elevation angle θ from the axis of the antenna and a plurality of electromagnetic waves **E1**, **E2** which emanate from the antenna as illustrated in FIG. **6**.

While FIG. **1** illustrates an embodiment with four segments and FIG. **4** two segments, it should be recognized that the invention can be carried out with any even number of segments, e.g. six segments. One advantage to increasing the number of segments will be to increase the radiated power and to reduce the composite impedance of the antenna feed ports and thereby simplify the task of matching impedance at the signal terminal to the composite impedance of the signal ports on the antenna. The advantage to reducing the number of segments is in reducing the overall size of the antenna.

While the primary design goal is to produce a vertically polarized omnidirectional radiation pattern as illustrated in FIG. **6**, it has been heretofore recognized through the principle of equivalence of electromagnetic systems and understanding of the elementary electric dipole antenna that this can be achieved through the creation of an azimuthal circular ring of magnetic current or flux. Therefore, the antenna will be discussed with respect to its ability to produce such a magnetic current distribution. With reference to FIG. **1**, a balanced signal is applied to the signal terminals **S1** and **S2**. This signal is then communicated to the toroidal helical feed ports a through d via balanced transmission lines. As is known from the theory of balanced transmission lines, at any given point along the transmission line, the currents in the two conductors are 180 degrees out of phase. Upon reaching the nodes to which the Transmission line connects, the current signal continues to propagate as a traveling wave in both directions away from each node. These current distributions along with their direction are shown in FIGS. **7** to **9** for a four segment and FIGS. **10–12** for the two segment antenna respectively and are referenced in these plots to the ports or nodes, where J refers to electric current and M refers to magnetic current. This analysis assumes that the signal frequency is tuned to the antenna structure such than the electrical circumference of the structure is one wavelength in length, and that the current distribution on the structure in sinusoidal in magnitude, which is an approximation. The contrawound toroidal helical winds of the antenna structure are treated as a transmission line, however these form a leaky transmission line due to the radiation of power. The plots of FIGS. **7** and **10** show the electric current distribution with polarity referenced to the direction of propagation away from the nodes from which the signals emanate. The plots of FIGS. **8** and **11** show the same current distribution when referenced to a common counter-clockwise direction, recognizing that the polarity of the current changes with respect to the direction to which it is referenced. FIGS. **9** and **12** then illustrate the corresponding magnetic current distribution utilizing the principles illustrated in FIG. **1**. FIGS. **8** and **11** show that the net electric current distribution on the toroidal helical structure is canceled. But as FIGS. **9** and **12** show, the net magnetic current distribution is enhanced. Thus those signals in quadrature sum up to form a quasi-uniform azimuthal current distribution.

The following five key elements should be satisfied to carry out the invention: 1) the antenna must be tuned to the signal frequency, i.e. at the signal frequency, the electrical circumferential length of each segment of the toroidal helical structure should be one quarter wavelength, 2) the signals at each node should be of uniform amplitude, 3) the signals at each port should be of equal phase, 4) the signal applied to the terminals **S1** and **S2** should be balanced, and 5) the impedance of the transmission line segments connecting the signal terminals **S1** and **S2** to the signal ports on the toroidal helical structure should be matched to the respective loads at each end of the transmission line segment in order to eliminate signal reflections.

When calculating the dimensions for the antenna, the following the following parameters are used in the equations that are used below.

a=the major axis of a torus;

b=the minor axis of the torus

D=2×b=minor diameter of the torus

N=the number of turns of the helical conductor wrapped around the torus;

n=number turns per unit length

V_g=the velocity factor of the antenna;

$a(\text{normalized})=a/\lambda=\tilde{a}$

$b(\text{normalized})=b/\lambda=b$

L_w=normalized conductor length

λ_g=the wavelength based on the velocity factor and λ for free space.

m=number of antenna segments

The toroidal helical antenna is at a "resonant" frequency as determined by the following three physical variables:

a=major radius of torus

b=minor radius of torus

N=number of radius of helical conductor wrapped around torus

V=guided wave velocity

It has been found that the number of independent variables can be further reduced to two, V_g and N, by normalizing the variables with respect to the free space wavelength λ, and rearranging to form functions a(V_g) and b(V_g, N). That is, this physical structure will have a corresponding resonant frequency, with a free space wavelength of λ. For a four segment antenna, resonance is defined as that frequency where the circumference of the torus' major axis is one wavelength long. In general, the resonant operating frequency is that frequency at which a standing wave is created on the antenna structure for which each segment of the antenna is ¼ guided wavelength long (i.e. each node **12** in FIG. **1** is at the ¼ guided wavelength). In this analysis, it is assumed that the structure has a major circumference of one wavelength, and that the feeds and windings are correspondingly configured.

The velocity factor of the antenna is given by:

$$V_g=\frac{V}{c}=\frac{2\pi a}{\lambda}=\frac{4}{m}\ \frac{L}{\lambda}=\frac{\lambda_g}{\lambda} \tag{1}$$

The physical dimensions of the torus may be normalized with respect to the free space wavelengths as follows:

$$\tilde{a}=\frac{a}{\lambda}\quad \tilde{b}=\frac{b}{\lambda} \tag{2}$$

The reference "Wide-Frequency-Range Tuned Helical Antennas and Circuits" by A. G. Kandoian and W. Sichak in Convention Record of the I.R.E., 1953 National Convention, Part 2—Antennas and Communications, pp. 42–47 presents a formula which predicts the velocity factor for a coaxial line with a monofilar linear helical inner conductor. Through substitution of geometric variables, this formula was transformed to a toroidal helical geometry in U.S. Pat. Nos. 4,622,558 and 4,751,515 to give:

$$V_g=\frac{1}{\sqrt{1+20\left(\frac{2bN}{L}\right)^{2.5}\left(\frac{2b}{\lambda}\right)^{.5}}} \tag{3}$$

While this formula is based upon a different physical embodiment than the invention described herein, it is useful with minor empirical modification as an approximate description of the present invention for purposes of design to achieve a given resonant frequency.

Substituting (1) and (2) into equation (3) and simplifying, gives:

$$V_g=\frac{1}{\sqrt{1+20\left(\frac{2\tilde{b}N}{.25mV_g}\right)^{2.5}(2\tilde{b})^{.5}}}=\frac{1}{\sqrt{1+160\left(\frac{N}{.25mV_g}\right)^{2.5\tilde{b}^3}}} \tag{4}$$

From equation (1) and (2), the velocity factor and normalized major radius are dime fly proportional to one another:

$$V_g=2\pi\tilde{a} \tag{5}$$

Thus, equations (4) and (5) may be rearranged to solve for the normalized major and minor torus radii in terms of V_g and N:

$$\tilde{a}=\frac{mV_g}{8\pi} \tag{6}$$

$$\tilde{b}=\left(\frac{(1-V_g^2)\sqrt{V_g}}{160\left(\frac{4}{m}N\right)^{2.5}}\right)^{\frac{1}{3}} \tag{7}$$

subject to the fundamental property of a torus that:

$$\frac{\tilde{b}}{\tilde{a}}=\frac{b}{a}\leqq 1 \tag{8}$$

Equations (2), (6), (7), (8) provide the fundamental, frequency independent design relationships. They can be used to either find the physical size of the antenna, for a given frequency of operation, velocity factor, and number of turns, or to solve the inverse problem of determining the operating frequency given an antenna of a specific dimension having a given number of helical turns.

A further constraint based upon the referenced work of Kandoian and Sichak may be expressed in terms of the normalized variables as follows:

$$\frac{nD^2}{\lambda}=\frac{4Nb^2}{L\lambda}=\frac{4N\tilde{b}^2}{.25mV_g}\leqq\frac{1}{5} \tag{9}$$

Rearranging this to solve for b, and substituting equation (7) gives:

$$\tilde{b}=\left(\frac{(1-V_g^2)\sqrt{V_g}}{160\left(\frac{4}{m}N\right)^{2.5}}\right)^{\frac{1}{3}}\leqq\left(\frac{mV_g}{80N}\right)^{\frac{1}{2}} \tag{10}$$

Rearranging equation (10) to separate variables gives:

$$\frac{1-V_g^2}{V_g}\leqq\frac{16}{\sqrt{5}}\ \frac{N}{m}=\alpha \tag{11}$$

The resulting quadratic equation can be solved to give:

$$V_g\geqq\frac{-\alpha+\sqrt{\alpha^2+4}}{2} \tag{12}$$

Also, from (6) and (8):

$$V_g\geqq\frac{8\pi\tilde{b}}{m} \tag{13}$$

Constraint (13), which is derived from constraint (8), appears to be more stringent than constraint (12).

The normalized length of the helical conductor is then given by:

$$\tilde{L}_w=2\pi\sqrt{(N\tilde{b})^2+\tilde{a}^2}=2\pi\tilde{b}\sqrt{N^2+\left(\frac{\tilde{a}}{\tilde{b}}\right)^2} \tag{14}$$

The wire length will be minimized when a=b and for the minimum number of turns, N. When a=b, then from (6)

$$\tilde{b}=\frac{mV_g}{8\pi} \tag{15}$$

and thus

$$\tilde{L}_w=\frac{mV_g}{4}\sqrt{N^2+1}>\frac{mV_gN}{4} \tag{16}$$

For a four segment antenna, m=4 and

$$\tilde{L}_w > V_g N \tag{17}$$

Substituting equation (15) into equation (10) gives

$$V_g N = \left(\frac{\pi^3}{10\sqrt{m}} (1 - V_g^2) \right)^{0.4} \tag{18}$$

For minimum wire length, N=minimum=4, so for a four segment antenna,

$$V_g N = 1.151 < \tilde{L}_w \tag{19}$$

In general, the wire length will be smallest for small velocity factors, so equation (18) may be approximated as

$$V_g N \approx \left(\frac{\pi^3}{10\sqrt{m}} \right)^{0.4} \tag{20}$$

which when substituted into equation (16) gives

$$L_w > m^{.8} \left(\frac{\pi^3}{320} \right)^{0.4} = 0.393\, m^{.8} \tag{21}$$

Thus for all but two segment antennas, the equations of Kandoian and Sichak predict that the total wire length per conductor will be greater than the free space wavelength.

From these equations, one can construct a toroid that effectively has the transmission characteristics of a half wave antenna linear antenna. Experience with a number of contrawound toroidal helical antennas constructed according to this invention has shown that the resonant frequency of a given structure differs from that predicted by equations (2), (6) and (7) and in particular the actual remnant frequency appears to correspond to that predicted by equations (2), (6) and (7) when the number of turns N used in the calculations is larger by a factor of two to three than the actual number of turns for one of the two conductors. In some cases, the actual operating frequency appears to be best correlated with the length of wire. For a given length of toroidal helical conductor $L_w(a,b,N)$, this length will be equal to the free space wavelength of an electromagnetic wave whose frequency is given by:

$$f_w(a, b, N) = \frac{c}{L_w(a, b, N)} \tag{22}$$

In some cases, the measured resonant frequency was best predicted by either 0.75*f_w(a,b,N) or f_w(a,b,2N). For example, at a frequency of 106 Mhz a linear half wave antenna would be 55.7" long assuming a velocity factor of 1.0 whereas a toroid design embracing the invention would have the following dimensions.

a=2,738"

b=0.563"

N=16 turns #16 wire

m=4 segments

For this embodiment of the toroidal design, equations (2), (6) and (7) predict a remnant frequency of 311.5 MHz and Vg=0.454 for N=16 and 166.7 MHz for N=32. At the measured operating frequency, Vg=0.154 and for equation (4) to hold, the effective value of N must be 51 turns, which is a factor of 3.2 larger than the actual value for each conductor. In this case, f_w(a,b,2N)=103.2 MHz.

In a variation on the invention shown in FIG. **5**, the connections at the two ports a and c to the input signal are broken, as are the conductors at the corresponding nodes. The remaining four open ports **a11–a21**, **a12–a22**, **c11–c21** and **c21–c22** are then terminated with a reactance Z whose impedance is matched to the intrinsic impedance of the transmission line segments formed by the contrawound toroidal helical conductor pairs. The signal reflections from these terminal reactances act (see FIG. **13**) to reflect a signal which is in phase quadrature to the incident signals, such than the current distributions on the toroidal helical conductor are similar to those of the embodiment of FIG. **1**, thus providing the same radiation pattern but with fewer feed connections between the signal terminals and the signal ports which simplifies the adjustment and tuning of the antenna structure.

The toroidal contrawound conductors may be arranged in other than a helical fashion and still satisfy the spirit of this invention. FIG. **14** shows one such alternate arrangement (a "poloidal-peripheral winding pattern"), whereby the helix formed by each of the two insulated conductors **W1**. **W2** is decomposed into a series of interconnected poloidal loops **14.1**. The interconnections form circular arcs relative to the major axis. The two separate conductors are everywhere parallel, enabling this arrangement to provide a more exact cancellation of the toroidal electric current components and more precisely directing the magnetic current components created by the poloidal loops. This embodiment is characterized by a greater interconductor capacitance which acts to lower the resonant frequency of the structure as experimentally verified. The resonant frequency of this embodiment may be adjusted by adjusting the spacing between the parallel conductors **W1** and **W2**, by adjusting the relative angle of the two contrawound conductors with respect to each other and with respect to either the major or minor axis of the torus. The signals at each of the signal ports **S1**, **S2** should be balanced with respect to one another (i.e. equal magnitude with uniform 180° phase difference) magnitude and phase in order to carry out the invention in the best mode. The signal feed transmission line segments should also be matched at both ends, i.e. at the signal terminal common junction and at each of the individual signal ports on the contrawound toroidal helical structure. Imperfections in the contrawound windings, in the shape of the form upon which they are wound, or in other factors may cause variations in impedance at the signal ports. Such variations may require compensation such as in the form illustrated in FIG. **15** so that the currents entering the antenna structure are of balanced magnitude and phase so as to enable the most complete cancellation of the toroidal electric current components as described below. In the simplest form, if the impedance at the signal terminals is Z_0, typically 50 Ohms, and the signal impedance at the signal ports were a value of Z_1–m*Z_0, then the invention would be carried out with m feed lines each of equal length and of impedance Z_1 such that the parallel combination of these impedances at the signal terminal was a value of Z_0. If the impedance at the signal terminals were a resistive value Z_1 different from above, the invention could be carried out with quarter wave transformer feed lines, each one quarter wavelength long, and having an intrinsic impedance of Z_f=Z_0Z_1. In general, any impedances could be matched with double stub tuners constructed from transmission line elements. The feed lines from the signal terminal could be inductively coupled to the signal ports as shown in FIG. **16**. In addition to enabling the impedance of the signal ports to be matched to the feed line, this technique also acts as a balun to convert an unbalanced signal at the feed terminal to a balanced signal at the signal ports on the contrawound toroidal helical structure. With this inductive coupling approach, the coupling coefficient between the signal feed and the antenna structure may be adjusted so as to enable the antenna structure to resonate freely. Other means of impedance, phase, and amplitude matching and balancing familiar to those skilled in the art are also possible without departing from the spirit of this invention.

The antenna structure may be tuned in a variety of manners. In the best mode, the means of tuning should be uniformly distributed around the structure so as to maintain a uniform azimuthal magnetic ting current. FIG. **17** illustrates the use of poloidal foil structures **18.1**, **19.1** (see FIGS. **18** and **19**) surrounding the two insulating conductors which act to modify the capacitive coupling between the two helical conductors. The poloidal tuning elements may either be open or closed loops, the latter providing an additional inductive coupling component. FIG. **20** illustrates a means of balancing the signals on the antenna structure by capacitively coupling different nodes, and in particular diametrically opposed nodes on the same conductor. The capacitive coupling, using a variable capacitor C1, may be azimuthally continuous by use of a circular conductive foil or mesh, either continuous or segmented, which is parallel to the surface of the toroidal form and of toroidal extent. The embodiments in FIGS. **23** and **25** result from the extension of the embodiments of either FIGS. **17–21**, wherein the entire toroidal helical structure HS is surrounded by a shield **22.1** which is everywhere concentric. Ideally, the toroidal helical structure HS produces strictly toroidal magnetic fields which are parallel to such a shield, so that for a sufficiently thin foil for a given conductivity and operating frequency, the electromagnetic boundary conditions are satisfied enabling propagation of the electromagnetic field outside the structure. A slot (poloidal) **25.1** may be added for tuning as explained herein.

The contrawound toroidal helical antenna structure is a relatively high Q resonator which can serve as a combined tuning element and radiator for an FM transmitter as shown in FIG. **26** having an oscillator amplifier **26.2** to receive a voltage from the antenna **10**. Through a parametric tuning element **26.3** controlle by modulation may **26.4**, modulation may be accomplished. The transmission frequency F1 is controlled by electronic adjustment of a capacitive or inductive tuning element attached to the antenna structure by either direct modification of reactance or by switching a series fixed reactive elements (discussed previously) so as to control the reactance which is coupled to the structure, and hence adjust the natural frequency of the contrawound toroidal helical structure.

In another variation of the invention shown in FIG. **27**, the toroidal helical conductors of the previous embodiments are replaced by a series of N poloidal loops **27.1** uniformly azimuthally spaced about a toroidal form. The center most potions of each loop relative to the major radius of the torus are connected together at the signal terminal S1, while the remaining outer most portions of each loop are connected together at signal terminal S2. The individual loops while identical with one another may be of arbitrary shape, with FIG. **28** illustrating a circular shape, and FIG. **30** illustrating a rectangular shape. The electrical equivalent circuit for this configuration is shown in FIG. **29**. The individual loop segments each act as a conventional loop antenna. In the composite structure, the individual loops are fed in parallel so that the resulting magnetic field components created thereby in each loop are in phase and azimuthally directed relative to the toroidal form resulting in an azimuthally uniform ring of magnetic current. By comparison, in the contrawound toroidal helical antenna, the fields from the toroidal components of the contrawound helical conductors are canceled as if these components did not exist, leaving only the contributions from the poloidal components of the conductors. The embodiment of FIG. **27** thus eliminates the toroidal components from the physical structure rather than rely on cancellation of the correspondingly generated electromagnetic fields. Increasing the number of poloidal loops in the embodiment of FIG. **27** results in the embodiments of FIG. **31** and **33** for loops of rectangular and circular profile respectively. The individual loops become continuous conductive surfaces, which may or may not have radial plane slots so as to emulate a multi-loop embodiment. These structures create azimuthal magnetic ring currents which are everywhere parallel to the conductive toroidal surface, and whose corresponding electric fields are everywhere perpendicular to the conductive toroidal surface. Thus the electromagnetic waves created by this structure can propagate through the conductive surface given that the surface is sufficiently thin for the case of a continuous conductor. This device will have the effect of a ring of electric dipoles in moving charge between the top and bottom sides of the structure, i.e. parallel to the direction of the major axis of the toroidal form.

The embodiments of FIGS. **27** and **31** share the disadvantage of relatively large size because of the necessity for the loop circumference to be on the order of one half wavelength for resonant operation. However, the loop size may be reduced by adding either series inductance or parallel reactance to the structures of FIGS. **27** and **31**. FIG. **34** illustrates the addition of series inductance by forming the central conductor of the embodiment of FIG. **31** into a solenoidal inductor **35.1**. FIG. **36** illustrates the addition of parallel capacitance **36.1** to the embodiment of FIG. **31**. The parallel capacitor is in the form of a central hub **36.2** for the toroid structure TS which also serves to provide mechanical support for both the toroidal form and for the central electrical connector **36.3** by which the signal at terminals S1 and S2 is fed to the antenna structure. The parallel capacitor and structural hub are formed from two conductive plates P1 and P2, made from copper, aluminum or some other nonferrous conductor, and separated by a medium such as air, Teflon, polyethylene or other low loss dielectric material **36.4**. The connector **36.3** with terminals S1 and S2 is conductively attached to and at the center of parallel plates P1 and P2 respectively, which are in turn conductively attached to the respective sides of a toroidal slot on the interior of the conductive toroidal surface TS. The signal current flows radially outward from connector **36.3** through plates P1 and P2 and around the conductive toroidal surface TS. The addition of the capacitance provided by conductive plates P1 and P2 enables the poloidal circumference of the toroidal surface TS to be significantly smaller than would otherwise be required for a similar state of resonance by a loop antenna operating at the same frequency.

The capacitive tuning element of FIG. **36** may be combined with the inductive loops of FIG. **27** to form the embodiment of FIG. **37**, the design of which can be illustrated by assuming for the equivalent circuit of FIG. **38** that all of the capacitance in the is provided by the parallel plate capacitor, and all of the inductance is provided by the wire loops. The formulas for the capacitance of a parallel plate capacitor and for a wire inductor are given in the reference *Reference Data for Radio Engineers, 7th ed.*, E. C. Jordan ed., 1986, Howard W. Sams, p. 6–13 as:

$$C = 0.225\epsilon_r\left[(N-1)\frac{A}{t}\right] \tag{23}$$

-continued

and

$$L_{wire}=\frac{a}{100}\left[7.353\mathrm{Log}_{10}\left(16\frac{a}{d}\right)-6.386\right] \tag{24}$$

where

C=capacitance pfd
L_{wire}=inductance µH
A=plate area in^2
t=plate separation in.
N=number of plates
a=mean radius of wire loop in.
d=wire diameter in.
ϵ_r=relative dielectric constant

The resonant frequency of the equivalent parallel circuit, assuming a total of N wires, is then given by:

$$\omega=\frac{1}{\sqrt{L_{total}C}}=\frac{1}{\sqrt{\frac{L_{wire}}{N}C}} \tag{25}$$

$$f=\frac{\omega}{2\pi} \tag{26}$$

For a toroidal form with a minor diameter=2.755 in. and a major inside diameter (diameter of capacitor plates) of 4.046 in. for N=24 loops of 16 gauge wire (d=0.063 in.) with a plate separation of t=0.141 in. gives a calculated resonant frequency of 156.5 MHz.

For the embodiment of FIG. **38**, the inductance of a single turn toroidal loops is approximated by:

$$L=\frac{\mu_0 b^2}{2a} \tag{27}$$

where μ_0 is the permeability of free space=400πnH/m, and a and b are the major and minor radius of the toroidal form respectively. The capacitance of the parallel plate capacitor formed as the hub of the torus is given by:

$$C=\epsilon_0\epsilon_r\frac{A}{t}=\epsilon_0\epsilon_r\frac{\pi(a-b)^2}{t} \tag{28}$$

here ϵ_0 is the permitivity of free space=8.854 pfd./m.

Substituting equations (27) and (28) into equations (25) and (26) gives:

$$f=\frac{38.07}{\sqrt{\frac{b^2(a-b)^2\epsilon_r}{at}}}\text{ MHz} \tag{29}$$

Equation (29) predicts that the toroidal configuration illustrated above except for a continuous conductive surface will have the same resonant frequency of 156.5 MHz if the plate separation is increased to 0.397 in.

The embodiments of FIGS. **36**, **37** and **38** can be tuned by adjusting either the entire plate separations, or the separation of a relatively narrow annular slot from the plate as shown in FIG. **38**, where this fine tuning means is azimuthally symmetric so as to preserve symmetry in the signals which propagate radially outward from the center of the structure.

FIGS. **39** and **41** illustrate means of increasing the bandwidth of this antenna structure. Since the signals propagate outward in a radial direction, the bandwidth is increased by providing different differential resonant circuits in different radial directions. The variation in the geometry is made azimuthally symmetric so as to minimize geometric perturbation to the azimuthal magnetic field. FIGS. **39** and **41** illustrate geometries which are readily formed from commercially available tubing fittings, while FIG. **25** (or FIG. **24**) illustrates a geometry with a sinusoidally varying radius which would reduce geometric perturbations to the magnetic field.

The prior art of helical antennas show their application in remote sensing of geotechnical features and for navigation therefrom. For this application, relatively low frequencies are utilized necessitating large structures for good performance. The linear helical antenna is illustrated in FIG. **43**. This can be approximated by FIG. **44** where the true helix is decomposed in to a series of single turn loops separated by linear interconnections. If the magnetic field were uniform or quasi-uniform over the length of this structure, then the loop elements could be separated from the composite linear element to form the structure of FIG. **45**. This structure can be further compressed in size by then substituting for the linear element either the toroidal helical or the toroidal poloidal antenna structures described herein, as illustrated in FIG. **46**. The primary advantage to this configuration is that the overall structure is more compact than the corresponding linear helix which is advantageous for portable applications as in air, land or sea vehicles, or for inconspicuous applications. A second advantage to this configuration, and to that of FIG. **45** is that the magnetic field and electric field signal components are decomposed enabling them to be subsequently processed and recombined in a manner different from that inherent to the linear helix but which can provide additional information.

Referring to FIG. **48**, a schematic of an electromagnetic antenna **48** is illustrated. The antenna **48** includes a surface **49**, such as the toroid form TF of FIG. **1**; an insulated conductor circuit **50**; and two signal terminals **52**,**54**, although the invention is applicable to a wide variety of surfaces such as, for example, a multiply connected surface, a generally spherical surface (as shown with FIG. **59**), a spherical surface (as shown with FIG. **66**), or a hemispherical surface (as shown with FIG. **68**).

As employed herein the term "multiply connected surface" shall expressly include, but not be limited to: (a) any toroidal surface such as the toroid form TF of FIG. **1** having its major radius greater than or equal to its minor radius; (b) other surfaces formed by rotating a circle, or a plane closed curve or polygon having a plurality of different radii about an axis lying on its plane, with such other surfaces' major radius being greater than zero, and with such other surfaces' minor radius being less than, equal to or greater than the major radius; and (c) still other surfaces such as surfaces like those of a washer or nut such as a hex nut formed from a generally planar material in order to define, with respect to its plane, an inside circumference greater than zero and an outside circumference greater than the inside circumference, with the outside and inside circumferences being either a plane closed curve and/or a polygon.

The exemplary insulated conductor circuit **50** extends in a conductive path **56** around and over the surface **49** from a node **60** (+) to another node **62** (–). The insulated conductor circuit **50** also extends in another conductive path **58** around and over the surface **49** from the node **62** (–) to the node **60** (+) thereby forming a single endless conductive path around and over the surface **49**.

As discussed above in connection with FIG. **1**, the conductive paths **56**,**58** may be contrawound helical conductive paths having the same number of rams, with the helical pitch sense for the conductive path **56** being right hand (RH), as shown by the solid line, and the helical pitch sense for the conductive path **58** being left hand (LH) which is opposite from the RH pitch sense, as shown by the broken lines.

The conductive paths **56**,**58** may be arranged in other than a helical fashion, such as a generally helical fashion, a partially helical fashion, a poloidal-peripheral pattern, or a spiral fashion, and still satisfy the spirit of this invention. The conductive paths **56**,**58** may be contrawound "poloidal-peripheral winding patterns" having opposite winding senses, as discussed above in connection with FIG. **14**, whereby the helix formed by each of the two insulated conductors **W1**,**W2** is decomposed into a series of interconnected poloidal loops **14.1**.

Continuing to refer to FIG. **48**, the conductive paths **56**,**58** reverse sense at the nodes **60**,**62**. The signal terminals **52**,**54** are respectively electrically connected to the nodes **60**,**62**. The signal terminals **52**,**54** either supply to or receive from the insulated conductor circuit **50** an outgoing (transmitted) or incoming (received) RF electrical signal **154**. For example, in the case of a transmitted signal, the single endless conductive path of the insulated conductor circuit **50** is fed in series from the signal terminals **52**,**54**.

It will be appreciated by those skilled in the art that the conductive paths **56**,**58** may be formed by a single insulated conductor, such as, for example, a wire or printed circuit conductor, which forms the single endless conductive path including the conductive path **56** from the node **60** to the node **62** and the conductive path **58** from the node **62** back to the node **60**. It will be further appreciated by those killed in the art that the conductive paths **56**,**58** may be formed by plural insulated conductors such as one insulated conductor which forms the conductive path **56** from the node **60** to the node **62**, and another insulated conductor which forms the conductive path **58** from the node **62** back to the node **60**.

The nominal operating frequency of the signal **64** is tuned to the structure of the antenna **48** in order that the electrical circumference thereof is one-half wavelength in length, and that the current distribution on the structure is sinusoidal in magnitude, which is an approximation. The contrawound conductive paths **56**,**58**, which each have a length of about one-half of a guided wavelength of the nominal operating frequency, may be viewed as elements of a non-uniform transmission line with a balanced feed. The paths **56**,**58** form a closed loop that, for example, in the case of a toroidal surface such as the toroid form TF of FIG. **1**, has been twisted to form a "figure-8" and then folded back on itself to form two concentric windings.

Referring to FIG. **49**, a schematic of another electromagnetic antenna **48'** is illustrated. The antenna **48'** includes a surface such as the surface **49** of FIG. **48**, an insulated conductor circuit **50'**, and two signal terminals **52'**,**54'**. Except as discussed herein, the electromagnetic antenna **48'**, insulated conductor circuit **50'**, and signal terminals **52'**,**54'** are generally the same as the respective electromagnetic antenna **48**, insulated conductor circuit **50**, and signal terminals **52**,**54** of FIG. **48**.

The exemplary insulated conductor circuit **50'** extends in a conductive path **56'** around and over the surface **49** from a node **60'** (+) to an intermediate node A and from the intermediate node A to another node **62'** (−). The insulated conductor circuit **50'** also extends in another conductive path **58'** around and over the surface **49** from the node **62'** (−) to another intermediate node B and from the intermediate node B to the node **60'** (+) thereby forming a single endless conductive path around and over the surface **49**.

As discussed above in connection with FIGS. **14** and **48**, the conductive paths **56'**,**58'** may be contrawound helical conductive paths having the same number of turns or may be arranged in other than a purely helical fashion such as a generally helical fashion, a partially helical fashion, a spiral fashion, or contrawound "poloidal-peripheral winding patterns" having opposite winding senses.

The signal terminals **52'**,**54'** either supply to or receive from the insulated conductor circuit **50'** an outgoing (transmitted) or incoming (received) RF electrical signal **64**. The conductive paths **56'**,**58'**, which each have a length of about one-half of a guided wavelength of the nominal operating frequency of the signal **64**, reverse sense at the nodes **60'**,**62'**. The signal terminals **52'**,**54'** are respectively electrically connected to the intermediate nodes A,B. Preferably, the nodes **60'**,**62'** are diametrically opposed to the intermediate nodes A,B in order that the length of the conductive paths **56'**,**58'** from the respective nodes **60'**,**62'**to to the respective intermediate nodes A,B is the same as the length of the conductive paths **56'**,**58'** from the respective intermediate nodes A,B to the respective nodes **62'**,**60'**.

It will be appreciated by those skilled in the art that the conductive paths **56'**,**58'** may be formed by a single insulated conductor which forms the single endless conductive path including the conductive path **56'** from the node **60'** to the intermediate node A and then to the node **62'**, and the conductive path **58'** from the node **62'** to the intermediate node B and then to the node **60'**. It will be further appreciated by those skilled in the art that each of the conductive paths **56'**,**58'** may be formed by one or more insulated conductors such as, for example, one insulated conductor from the node **60'** to the intermediate node A and from the intermediate node A to the node **62'**; or one insulated conductor from the node **60'** to the intermediate node A, and another insulated conductor from the intermediate node A to the node **62'**.

Referring to FIG. **50**, a schematic of another electromagnetic antenna **66** is illustrated. The antenna **66** includes a surface such as the surface **49** of FIG. **48**, a first insulated conductor circuit **68**, a second insulated conductor circuit **70**, and two signal terminals **72**,**74**.

The insulated conductor circuit **68** includes a pair of helical conductive paths **76**,**78**, and the insulated conductor circuit **70** similarly includes a pair of helical conductive paths **80**,**82**. The insulated conductor circuit **68** extends in the conductive path **76** around and partially over the surface **49** from a node **84** to a node **86**, and also extends in the conductive path **78** around and partially over the surface **49** from the node **86** to the node **84** in order that the conductive paths **76**,**78** form an endless conductive path around and over the surface **49**. The insulated conductor circuit **70** extends in the conductive path **80** around and partially over the surface **49** from a node **88** to a node **90**, and also extends in the conductive path **82** around and partially over the surface **49** from the node **90** to the node **88** in order that the conductive paths **80**,**82** form another endless conductive path around and over the surface **49**.

As discussed above in connection with FIGS. **14** and **48**, the conductive paths **76**,**78** and **80**,**82** may be contrawound helical conductive paths having the same number of rams or may be arranged in other than a purely helical fashion such as a generally helical fashion, a partially helical fashion, a spiral fashion, or contrawound "poloidal-peripheral winding patterns" having opposite winding senses. For example, the pitch sense of the conductive path **76** may be right hand (RH), as shown by the solid line, the pitch sense for the conductive path **78** being left hand (LH) which is opposite from the RH pitch sense, as shown by the broken lines, and the pitch sense for the conductive paths **80** and **82** being LH and RH, respectively. The conductive paths **76**,**78** reverse sense at the nodes **84** and **86**. The conductive paths **80**,**82** reverse sense at the nodes **88** and **90**.

The signal terminals **72**,**74** either supply to or receive from the insulated conductor circuits **68**,**70** an outgoing (transmitted) or incoming (received) RF electrical signal **92**.

For example, in the case of a transmitted signal, the pair of endless conductive paths of the insulated conductor circuits **68,70** are fed in series from the signal terminals **72,74**, although the invention is applicable to parallel feeds at both the nodes **84,88** and the nodes **90,86**. Each of the conductive paths **76,78,80,82** have a length of about one-quarter of a guided wavelength of the nominal operating frequency of the signal **92**. As shown in FIG. **50**, the signal terminal **72** is electrically connected to the node **84** and the signal terminal **74** is electrically connected to the node **88**.

It will be appreciated by those skilled in the art that the insulated conductor circuits **68,70** may each be formed by one or more insulated conductors. For example, the insulated conductor circuit **68** may have a single conductor for both of the conductive paths **76,78**; a single conductor for each of the conductive paths **76,78**; or multiple electrically interconnected conductors for each of the conductive paths **76,78**.

Referring to FIG. **51**, a representative elevation radiation pattern for the electromagnetic antennas **48,48',66** of FIGS. **48,49,50**, respectively, is illustrated. These antennas are linearly (e.g., vertically) polarized and have a physically low profile, associated with the minor diameter of the surface **49** of FIGS. **48,49,50**, along the direction of polarization. Furthermore, such antennas are generally omnidirectional in directions that are normal to the direction of polarization, with a maximum radiation gain in directions normal to the direction of polarization and a minimum radiation gain in the direction of polarization. The contrawound conductive paths, such as the conductive paths **56,58** of FIG. **48**, provide destructive interference which cancels the resulting electrical fields and constructive interference which reinforces the resulting magnetic fields.

Referring to FIGS. **52** and **53**, an electromagnetic antenna **94** includes a toroidal antenna **96**, such as the antennas **10,48,48',66** of respective FIGS. **1,48,49,50**; and a parabolic reflector **98**, such as a satellite dish reflector, which directs antenna signals **100,102** with respect to the toroidal surface **103** of the antenna **96** for reception or transmission of the antenna signals **100,102**, although the invention is more generally applicable to multiply connected surfaces and various types of reflectors. The parabolic reflector **98** has a generally parabolic shape with a vertex **104**, an opening **106**, and a central axis **108** between the vertex **104** and the opening **106**. The parabolic reflector **98** further has a focal point **110** on the central axis **108**.

The toroidal surface **103** is located generally between the vertex **104** and the parabolic reflector opening **106**. Preferably, the major axis of the toroidal surface **103** is located along the central axis **108** of the parabolic reflector **98**, with the center of the toroidal surface **103** being located at the focal point **110** of the parabolic reflector **98**.

The electromagnetic antenna **94** provides directionality for the exemplary toroidal antenna **96**. The parabolic reflector **98** directs the desired electromagnetic signals **100,102** to the high gain portions **111** of the field pattern **112** of the antenna **96**. Other undesired signals **114,116** respectively either encounter the low gain portions **118,119** of the field pattern **112** of the antenna **96** or else are deflected by the parabolic reflector **98**, such as at a point **120**.

Referring to FIGS. **54** and **55**, an electromagnetic antenna **94'**to includes the toroidal antenna **96** of FIGS. **52–53**, and a parabolic reflector **98'** which directs the antenna signals **100,102** in a similar manner as discussed above in connection with FIG. **53**. The parabolic reflector **98'** has an opening **122** and a generally parabolic shape **124** (shown in phantom line drawing) which defines a vertex **104** at about the center of the opening **122**. The other opening **106** of the parabolic reflector **98'** is larger than the opening **122**. The toroidal surface **103** is located generally between the openings **106,122** of the parabolic reflector **98'**. Except for the opening **122**, the parabolic reflector **98'** is generally similar to the parabolic reflector **98** of FIGS. **52–53**.

The exemplary parabolic reflector **98'** in general, and the opening **122** thereof in particular, take advantage of the field pattern **112** of the antenna **96**. The low gain portion **119** at the bottom (with respect to FIG. **55**) of the antenna **96** does not significantly contribute to transmission or reception of the antenna signals **100,102**. Accordingly, the absence of the surface of the parabolic reflector **98'** at the opening **122** thereof does not significantly affect the transmission or reception of the antenna signals **100,102**. An undesired signal toward the opening **122** bottom of FIG. **55**) toward the opening **122** merely encounters the low gain potion **119** of the antenna **96**. The absence of the surface of the parabolic reflector **98'** at the opening **122** greatly enhances the aerodynamic properties of the electromagnetic antenna **94'** for installations in high wind, such as on a motor vehicle or ship, thereby reducing wind drag and, hence, the requisite weight and structural strength of the parabolic reflector **98'** needed to resist such wind.

Referring to FIG. **56**, an electromagnetic antenna **128** includes a surface, such as the generally cylindrical surface **130** having a bore **132**, an upper surface **134** and a lower surface **136**, although the invention is applicable to other multiply connected surfaces such as a generally toroidal surface having a generally flat upper surface **134** and/or lower surface **136**. The antenna **128** includes a first insulated conductor circuit **138** which extends in a partially helical conductive path around and at least partially over the surface **130** with at least a first helical pitch sense, (e.g., right hand (RH)). The antenna **128** also includes a second insulated conductor circuit **140** which extends in another partially helical conductive path around and at least partially over the surface **130** with at least a second helical pitch sense (e.g., left hand (LH)), in order that the insulated conductor circuits **138,140** are contrawound relative to each other around and at least partially over the surface **130**.

The major axis **142** of the electromagnetic antenna **128** is generally perpendicular with respect to the upper surface **134** and the lower surface **136**. The insulated conductor circuits **138,140** are generally radial with respect to the major axis **142** as shown with the radial portions **144,146**, respectively, on the upper surface **134**. The insulated conductor circuits **138,140** are also generally radial with respect to the major axis **142** as shown with the radial portions **148,150** (shown in hidden line drawing), respectively, on the lower surface **136**. Otherwise, the insulated conductor circuits **138,140** are generally helically oriented as shown with the generally helical portions **152,154**, respectively, on the outer surface **156** of the generally cylindrical surface **130** a well as with the generally helical portions **156,158**, respectively, within the bore **132** of the generally cylindrical surface **130**. Those skilled in the art will appreciate that the exemplary generally cylindrical surface **130** and the insulated conductor circuits **138,140** with the radial portions **144,146,148,150** and generally helical portions **152,154, 156,158** may be employed with the antennas **10,48,48',66** of respective FIGS. **1,48,49,50**.

FIG. **57** illustrates a representative elevation radiation pattern for the antennas **10,48,48',66** of respective FIGS. **1,48,49,50** employing a toroidal surface with helical conductive paths. Also referring to FIG. **58**, the exemplary electromagnetic antenna **128** of FIG. **56** radiates or receives more energy radially and, therefore, less energy is radiated or received vertically. Accordingly, in this embodiment, the radiation pattern on the top and bottom of the antenna **128** is further reduced, in comparison with antennas having helical conductive paths, and the radial radiation pattern is enhanced. Furthermore, the exemplary insulated conductor circuits **138**,**140**, which utilize some linear conductor portions **144**,**146**,**148**,**150**, reduce the relative size of the major radius of the antenna **128**.

Referring to FIG. **59**, an electromagnetic antenna **160** includes a generally spherical toroid form surface **162** with a generally circular cross section **164** (as shown by various lines of latitude) and a conduit **166** (shown in hidden line drawing) along the major axis **168** of the surface **162**. The antenna **160** includes a first insulated conductor circuit **170** which extends in a first partially helical conductive path **172** around and at least partially over the generally spherical surface **162** with at least a first helical pitch sense (e.g., RH). The antenna **160** also includes a second insulated conductor circuit **174** which extends in a second partially helical conductive path **176** around and at least partially over the generally spherical surface **162** with at least a second helical pitch sense (e.g., LH), in order that the first and second insulated conductor circuits **170**,**174** are contrawound relative to each other around and at least partially over the generally spherical surface **162**. The partially helical conductive paths **172**,**176** pass through the conduit **166** and are generally parallel to the major axis **168** within the conduit **166** as shown with the generally linear portions **178**,**180** of the respective paths **172**,**176**. Otherwise, the paths **172**,**176** have respective generally helical portions **182**,**184**. Those skilled in the art will appreciate that the exemplary generally spherical surface **162** and the insulated conductor circuits **170**,**174** with the generally linear portions **178**,**180** and generally helical portions **182**,**184** may be employed with the antennas **10**,**48**,**48'**,**66** of respective FIGS. **1**,**48**,**49**,**50**.

FIG. **60** illustrates a representative elevation radiation pattern for the antennas **10**,**48**,**48'**,**66** of respective FIGS. **1**,**48**,**49**,**50** employing a toroidal surface with helical conductive Paths. Also referring to FIG. **61**, the exemplary electromagnetic antenna **160** of FIG. **59** radiates or receives more energy vertically. Therefore, in this embodiment, the radiation pattern on the top and bottom of the antenna **160** is enhanced, in comparison with antennas having helical conductive paths. In this manner, this embodiment produces a somewhat more symmetrical radiation pattern.

FIG. **62** illustrates a vertical sectional perspective view of a toroid form **186** in which the minor radius is greater than the major radius thereof, although the invention is applicable to any multiply connected surface having a major radius which is greater than zero and a minor radius which is greater than the major radius. Also referring to FIGS. **63** and **64**, respective plan and perspective views illustrate the path of an insulated conductor circuit **188** having four turns **190**,**192**,**194**,**196**, although the invention is applicable to insulated conductor circuits having any number of turns. Employed with the exemplary toroid form **186**, the insulated conductor circuit **188** extends in a generally helical conductive path around and at least partially over the surface **197** of the exemplary toroid form **186**, in a manner described below, with at least a first helical pitch sense (e.g. RH). Also referring to FIG. **65**, another insulated conductor circuit **198** having four turns **200**,**202**,**204**,**206** may also be employed with the exemplary toroid form **186**. The second insulated conductor circuit **198** extends in a generally helical conductive path around and at least partially over the surface **197** of the toroid form **186** with at least a second helical pitch sense (e.g. LH), in order that the insulated conductor circuits **188**,**198** are contrawound relative to each other around and at least partially over the surface **197** of the toroid form **186**.

The surface **197** of the toroid form **186** may be implemented, for example, as a mesh screen surface having a plurality of openings **208** therein for routing the insulated conductor circuits **188**,**198** therethrough. In this exemplary manner, the central portion **210** of the toroid form **186** is accessible for routing the portions **211** (best shown in FIG. **63**) of the circuits **188**,**198** therein, although other implementations are possible such as, for example, assembling the toroid form **186** with a plurality of pie slices which form the central potion **210** and which provide routing channels for the circuits **188**,**198**; or drilling suitable routing holes into a solid toroid form.

Those skilled in the art will appreciate that the exemplary toroid form **186** and the exemplary insulated conductor circuits **188**,**198** may be employed with the antennas **10**,**48**, **48'**,**66** of respective FIGS. **1**,**48**,**49**,**50**. The circuits **188**,**198** pass through two common points **212**,**214** in the toroid form **186** at the respective portions **216**,**218** (shown in FIG. **65**) of the circuits **188**,**198**.

As schematically shown in FIG. **72**, the antenna **219**, which is similar to the antenna **10** of FIG. **1**, includes nodes **a1**,**b2**,**c1**,**d2** which converge (with smaller values of the major radius) at a terminal **220** and the nodes **a2**,**b1**,**c2**,**d1** similarly converge at a terminal **222**, where the lines between the nodes **a1**,**b2**,**c1**,**d2** and **a2**,**b1**,**c2**,**d1** are shown for convenience of illustration. In this manner, the antenna **219** has a single port at the terminals **220**,**222** or, alternatively, may be fed independently at each of the segments **12**. In turn, the terminals **220** and **222** are electrically connected to the respective nodes **a1**,**b2**,**c1**,**d2** and **a2**,**b1**,**c2**,**d1** which converge (with smaller values of the major radius) at substantially common points **212**,**214** along the major axis **224** of the toroid form **186**. The points **212**,**214** are associated with the respective portions **216**,**218** (shown in FIG. **65**) of the circuits **188**,**198**.

A three dimensional toroidal surface such as the toroid form TF of FIG. **1** may be represented by the following equations:

$$x=a\cos(\theta)+b\cos(\psi)\cos(\theta) \quad (30)$$

$$y=a\sin(\theta)+b\cos(\psi)\sin(\theta) \quad (31)$$

$$z=b\sin(\psi) \quad (32)$$

wherein:

a: major radius

b: minor radius

ϕ: poloidal angle (0 to 2π)

θ: azimuthal angle (0 to 2π)

A helix existing on the toroid form TF of FIG. **1** is defined by setting:

$$\psi=N\theta \quad (33)$$

wherein:

N: number of turns in the helix

$N>0$: right hand (RH) windings

$N<0$: left hand (LH) windings

The equations defining a helix are:

$$x=a\cos(\theta)+b\cos(N\theta)\cos(\theta) \quad (34)$$

$$y=a\sin(\theta)+b\cos(N\theta)\sin(\theta) \quad (35)$$

$$z=b\sin(N\theta) \quad (36)$$

By taking N to be both positive and negative, Equations 34–36 adequately describe both contrawound windings.

Referring to FIGS. **66** and **67**, contrawound spherical conductors **226**,**228** for a spherical form antenna **230** having a spherical surface **232** are illustrated. Although a spherical surface is preferred, the invention is applicable to generally spherical surfaces. The conductor **226** extends in a first conductive path around and at least partially over the spherical surface **232** with at least a first winding sense (e.g., RH). The conductor **228** extends in a second conductive path around and at least partially over the spherical surface **232** with at least a second winding sense (e.g., LH), in order that the conductors **226**,**228** are contrawound relative to each other around and at least partially over the spherical surface **232**.

For the spherical embodiment, the equations describing the contrawound windings are developed by setting the major radius a to zero, as shown in the following equations:

$$x=b\cos(N\theta)\cos(\theta) \qquad (37)$$

$$y=b\cos(N\theta)\sin(\theta) \qquad (38)$$

$$z=b\sin(N\theta) \qquad (39)$$

A sphere provides the benefit of a more spherical radiation pattern, although the invention is applicable to generally spherical embodiments where the major radius is greater than zero. This approaches the radiation pattern of an ideal isotropic radiator or point source which projects energy equally in all directions. By employing the contrawound windings **226**,**228**, the electric fields cancel and leave a magnetic loop current of about zero radius. Those skilled in the art will appreciate that the exemplary spherical surface **232** and the exemplary contrawound windings **226**,**228** may be employed with the antennas **10**,**48**,**48'**,**66** of respective FIGS. **1**,**48**,**49**,**50** where, for example, polar nodes **233**A, **233**B of FIG. **67** facilitate changes between the winding senses (e.g., LH and RH) where the paths of the contrawound windings **226**,**228** generally repeatedly intersect thereabout.

Referring to FIG. **68**, contrawound hemispherical conductors **234**,**236** for a hemispherical form antenna **238** having a hemispherical surface **240** on a plane **242** are illustrated. For the hemispherical embodiment, the equations describing the contrawound windings are developed by Equations 37–39 above where z is greater than or equal to zero. The conductor **234** extends in a first conductive path around and at least partially over the hemispherical surface **240** with at least a first winding sense (e.g., RH) and the conductor **236** extends in a second conductive path around and at least partially over the hemispherical surface **240** with at least a second winding sense (e.g., LH), in order that the conductors **234**,**236** are contrawound relative to each other around and at least partially over the hemispherical surface **240**.

For clarity of description of the contrawound conductors and connections thereto, the plane **242** includes a left portion **244** and a fight portion **246**. At about the center of the plane **242** are a pair of terminals A,B of which terminal A is offset for convenience of illustration. A plurality of feeds **248** are connected to the terminal A and plurality of feeds **250** are connected to the terminal B. The feeds **248**,**250** are preferably shielded and have the same electrical impedance.

Preferably, the plane **242** is a ground plane which reflects each winding electrically and creates a mirror image thereof. In this manner, if the hemispherical form antenna **238** is on the bottom of an airplane or on the top of a ear, then, from a distance, the radiation pattern thereof approximates that of a spherical antenna.

On the right portion **246** of the plane **242**, the feeds **248**,**250** are connected to the conductors **236**,**234**, respectively. On the left portion **244** of the plane **242**, the feeds **248**,**250** are connected to the conductors **234**,**236**, respectively. The exemplary hemispherical antenna **238** is useful in stimulating or detecting earth currents, such as those employed in geophysical exploration, and generally projects or receives energy equally in all directions above the plane **242** of FIG. **68**.

Referring to FIGS. **69** and **70**, alternative contrawound spherical conductors **226'**,**228'** for the spherical surface **232** of FIG. **67** are illustrated. In this spherical embodiment, the spherical conductors **226'**,**228'** do not repeatedly cross at the poles as discussed in connection with FIG. **67**. The antenna **230'** is created, for example, by rotating the spherical surface **232** as the conductors **226'**,**228'** are applied.

Mathematically, a transformation matrix is introduced to operate on the position vector (x,y,z) defined by Equations 37–39. By applying the same transformation operator to both contrawound conductors **226'**,**228'** the transformation preserves the contrawound symmetry originally contained in the toroidal embodiment of Equations 34–36.

Equation **40** illustrates the general form of the transformed equations. The transformation matrix is, in general, a function of both ϕ and θ.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \tau_{11}(\theta,\phi) & \tau_{12}(\theta,\phi) & \tau_{13}(\theta,\phi) \\ \tau_{21}(\theta,\phi) & \tau_{22}(\theta,\phi) & \tau_{23}(\theta,\phi) \\ \tau_{31}(\theta,\phi) & \tau_{32}(\theta,\phi) & \tau_{33}(\theta,\phi) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (40)$$

wherein:

(X,Y,Z): transformed coordinates

(x,y,z): untransformed coordinates

τ_{ij}: general function of ϕ and θ.

The transformation matrix of Equation 40 is defined as being any matrix which preserves the contrawound symmetry of the windings. For example, the geometry of the contrawound conductors **226'**,**228'** may be distorted by stretching or rotation, although the invention is applicable to any windings providing destructive interference in order to cancel the resulting electrical fields and constructive interference in order to reinforce the resulting magnetic fields. In order to illustrate this transformation an example will be provided.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{\theta}{2}\right) & 0 & \sin\left(\frac{\theta}{2}\right) \\ 0 & 1 & 0 \\ -\sin\left(\frac{\theta}{2}\right) & 0 & \cos\left(\frac{\theta}{2}\right) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (41)$$

In this example, the spherical surface **232** is rotated in the XZ-plane as a function of θ, although the invention is applicable to a wide range of transformations associated with toroidal surfaces, multiply connected surfaces, generally spherical surfaces and spherical surfaces.

Referring to FIG. **71**, an antenna **254** having one or two feed ports is illustrated. The insulated conductor circuit **256** extends in the conductive path **258** around and partially over the surface **232** from a node **260** (+) to a node **262** (–). After changing winding sense at node **262** (–), the insulated conductor circuit **256** extends in the conductive path **274** around and partially over the surface **232** from the node **262**

(–) to the node **260** (+) in order that the conductive paths **258,274** form an endless conductive path around and over the surface **232**. The insulated conductor circuit **266** (shown in hidden line drawing) extends in the conductive path **268** around and partially over the surface **232** from a node **270** (–) to a node **272** (+). After changing winding sense at node **272** (+), the insulated conductor circuit **266** extends in the conductive path **264** around and partially over the surface **232** from the node **272** (+) to the node **270** (–) in order that the conductive paths **268,264** form another endless conductive path around and over the surface **232**.

The exemplary antenna **254** provides transmission and reception of antenna signals. For example, in the case of a transmitted signal, the pair of endless conductive paths of the insulated conductor circuits **256,266** are fed in series from the nodes **272,262**, although the invention is applicable to parallel feeds at both the nodes **272,262** and the nodes **260,270**.

In addition to modifications and variations discussed or suggested previously, one skilled in the art may be able to make other modifications and variations without departing from the true scope and spirit of the invention.

I claim:

1. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

   a multiply connected surface;

   first insulated conductor means extending in a first generally helical conductive path around and at least partially over said multiply connected surface with at least a first helical pitch sense;

   second insulated conductor means extending in a second generally helical conductive path around and at least partially over said multiply connected surface with at least a second helical pitch sense which is opposite from the first helical pitch sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said multiply connected surface;

   first and second signal terminals respectively electrically connected to said first and second insulated conductor means; and

   reflector means for directing said antenna signal with respect to said multiply connected surface for reception or transmission of the antenna signal.

2. The electromagnetic antenna of claim **1** wherein said reflector means includes a parabolic reflector.

3. The electromagnetic antenna of claim **2** wherein the parabolic reflector has a first opening, a generally parabolic shape which defines a vertex at about the first opening, and a second opening which is larger than the first opening; and wherein said multiply connected surface is located generally between the first and second openings of the parabolic reflector.

4. The electromagnetic antenna of claim **3** wherein the parabolic reflector further has a central axis between the first and second openings; and wherein said multiply connected surface has a major axis which is located generally along the central axis of the parabolic reflector.

5. The electromagnetic antenna of claim **4** wherein the parabolic reflector further has a focal point on the central axis thereof; and wherein said multiply connected surface is a toroidal surface having a major axis and a center thereon, with the center of the toroidal surface being located generally at the focal point of the parabolic reflector.

6. The electromagnetic antenna of claim **2** wherein said multiply connected surface is a toroidal surface; and wherein the parabolic reflector has a generally parabolic shape with a vertex and an opening; and wherein the toroidal surface is located generally between the vertex and the parabolic reflector opening.

7. The electromagnetic antenna of claim **2** wherein said multiply connected surface is a toroidal surface; wherein the parabolic reflector has a first opening, a generally parabolic shape which defines a vertex at about the first opening, and a second opening which is larger than the first opening; and wherein said toroidal surface is located generally between the first and second openings of the parabolic reflector.

8. The electromagnetic antenna of claim **2** wherein the parabolic reflector has a generally parabolic shape with a vertex and an opening; and wherein said multiply connected surface is located generally between the vertex and the parabolic reflector opening.

9. The electromagnetic antenna of claim **8** wherein the parabolic reflector further has an axis between the vertex and the opening; and wherein said multiply connected surface has a major axis which is located generally along the axis of the parabolic reflector.

10. The electromagnetic antenna of claim **9** wherein the parabolic reflector further has a focal point on the axis thereof; and wherein said multiply connected surface is a toroidal surface having a major axis and a center thereon, with the center of the toroidal surface being located generally at the focal point of the parabolic reflector.

11. The electromagnetic antenna of claim **1** wherein said first insulated conductor means extends in the first generally helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node; and wherein said second insulated conductor means extends in the second generally helical conductive path around and over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and second generally helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

12. The electromagnetic antenna of claim **1** wherein said first insulated conductor means extends in the first generally helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second generally helical conductive path around and over said multiply connected surface with the second helical pitch sense from the third node to a fourth node and from the fourth node to the first node in order that the first and second generally helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

13. The electromagnetic antenna of claim **1** wherein said first insulated conductor means extends in the first generally helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from a first node to a second node, and also extends in a third generally helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and third generally helical conductive paths form a first endless conductive path around and over said multiply

connected surface; and wherein said second insulated conductor means extends in the second generally helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from a third node to a fourth node, and also extends in a fourth generally helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from the fourth node to the third node in order that the third and fourth generally helical conductive paths form a second endless conductive path around und and over said multiply connected surface, with the first and third generally helical conductive paths being contrawound relative to the second and fourth generally helical conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal terminal is electrically connected to the second node.

14. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a multiply connected surface having a major axis and at least one generally flat surface which is generally perpendicular to the major axis;

first insulated conductor means extending in a first partially helical conductive path around and at least partially over said multiply connected surface with at least a first helical pitch sense;

second insulated conductor means extending in a second partially helical conductive path around and at least partially over said multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said multiply connected surface, with the first and second partially helical conductive paths, when generally perpendicular to the major axis of said multiply connected surface, being generally radial with respect to the major axis of said multiply connected surface, and otherwise being generally helically oriented; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means.

15. The electromagnetic antenna of claim **14** wherein said multiply connected surface is a generally cylindrical surface.

16. The electromagnetic antenna of claim **14** wherein said multiply connected surface is a generally toroidal surface.

17. The electromagnetic antenna of claim **14** wherein said first insulated conductor means extends in the first partially helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node; and wherein said second insulated conductor means extends in the second partially helical conductive path around and over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and second partially helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

18. The electromagnetic antenna of claim **14** wherein said first insulated conductor means extends in the first partially helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second partially helical conductive path around and over said multiply connected surface with the second helical pitch sense from the third node to a fourth node and from the fourth node to the first node in order that the first and second partially helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

19. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a multiply connected surface having a major axis;

first insulated conductor means extending in a first partially helical conductive path around and at least partially over said multiply connected surface with at least a first helical pitch sense;

second insulated conductor means extending in a second partially helical conductive path around and at least partially over said multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said multiply connected surface, with the first and second partially helical conductive paths, when generally perpendicular to the major axis of said multiply connected surface, being generally radial with respect to the major axis of said multiply connected surface, and otherwise being generally helically oriented; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means, wherein said first insulated conductor means extends in the partially helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from a first node to a second node, and also extends in a third partially helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and third partially helical conductive paths form a first endless conductive path around and over said multiply connected surface; and wherein said second insulated conductor means extends in the second partially helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from a third node to a fourth node, and also extends in a fourth partially helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from the fourth node to the third node in order that the third and fourth partially helical conductive paths form a second endless conductive path around and over said multiply connected surface, with the first and third partially helical conductive paths being contrawound relative to the second and fourth partially helical conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal terminal is electrically connected to the second node.

20. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a generally spherical surface having a conduit along a major axis thereof;

first insulated conductor means extending in a first partially helical conductive path around and at least partially over said generally spherical surface with at least a first helical pitch sense;

second insulated conductor means extending in a second partially helical conductive path around and at least partially over said generally spherical surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said generally spherical surface, with the first and second partially helical conductive paths passing through the conduit of said generally spherical surface and being generally parallel to the major axis thereof within the conduit, and otherwise being generally helically oriented; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means.

21. The electromagnetic antenna of claim **20** wherein said first insulated conductor means extends in the first partially helical conductive path around and over said generally spherical surface with the first helical pitch sense from a first node to a second node; and wherein said second insulated conductor means extends in the second partially helical conductive path around and over said generally spherical surface with the second helical pitch sense from the second node to the first node in order that the first and second partially helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said generally spherical surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

22. The electromagnetic antenna of claim **20** wherein said first insulated conductor means extends in the first partially helical conductive path around and over said generally spherical surface with the first helical pitch sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second partially helical conductive path around and over said generally spherical surface with the second helical pitch sense from the third node to a fourth node and from the fourth node to the first node in order that the first and second partially helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said generally spherical surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

23. The electromagnetic antenna of claim **20** wherein said first insulated conductor means extends in the first partially helical conductive path around and partially over said generally spherical surface with the first helical pitch sense from a first node to a second node, and also extends in a third partially helical conductive path around and partially over said generally spherical surface with the second helical pitch sense from the second node to the first node in order that the first and third partially helical conductive paths form a first endless conductive path around and over said generally spherical surface; and wherein said second insulated conductor means extends in the second partially helical conductive path around and partially over said generally spherical surface with the second helical pitch sense from a third node to a fourth node, and also extends in a fourth partially helical conductive path around and partially over said generally spherical surface with the first helical pitch sense from the fourth node to the third node in order that the third and fourth partially helical conductive paths form a second endless conductive path around and over said generally spherical surface, with the first and third partially helical conductive paths being contrawound relative to the second and fourth partially helical conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal is electrically connected to the second node.

24. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a multiply connected surface having a major radius which is greater than zero and a minor radius which is greater than the major radius;

first insulated conductor means extending in a first generally helical conductive path around and at least partially over said multiply connected surface with at least a first helical pitch sense;

second insulated conductor means extending in a second generally helical conductive path around and at least partially over said multiply connected surface with at least a second helical pitch sense, which is opposite from the first helical pitch sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said multiply connected surface; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means.

25. The electromagnetic antenna of claim **24** wherein said first insulated conductor means extends in the first generally helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node; and wherein said second insulated conductor means extends in the second generally helical conductive path around and over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and second generally helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

26. The electromagnetic antenna of claim **24** wherein said first insulated conductor means extends in the first generally helical conductive path around and over said multiply connected surface with the first helical pitch sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second generally helical conductive path around and over said multiply connected surface with the second helical pitch sense, from the third node to a fourth node and from the fourth node to the first node in order that the first and second generally helical conductive paths are contrawound relative to each other and form a single endless conductive path around and over said multiply connected surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

27. The electromagnetic antenna of claim **24** wherein said first insulated conductor means extends in the first generally helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from a first node to a second node, and also extends in a third generally helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from the second node to the first node in order that the first and third generally helical conductive paths form a first endless conductive path around and over said multiply connected surface; and wherein said second insulated conductor means extends in the second generally helical conductive path around and partially over said multiply connected surface with the second helical pitch sense from a third node to a fourth node, and also extends in a fourth generally helical conductive path around and partially over said multiply connected surface with the first helical pitch sense from the fourth node to the third node in order that the third and fourth generally helical conductive paths form a second endless conductive path around and over said multiply connected surface, with the first and third generally helical conductive paths being contrawound relative to the second and fourth generally helical conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal terminal is electrically connected to the second node.

28. The electromagnetic antenna of claim **24** wherein said first insulated conductor means extends in the first generally helical conductive path around and over said multiply connected surface and forms a first endless conductive path around and over said multiply connected surface, with the first generally helical conductive path having a first helical pitch sense and a second helical pitch sense, which is opposite from the first helical pitch sense; wherein said second insulated conductor means extends in the second generally helical conductive path around and over said multiply connected surface and forms a second endless conductive path around and over said multiply connected surface, with the second generally helical conductive path having the first and second helical pitch senses; wherein said first and second insulated conductor means are contrawound relative to each other in each of a plurality of adjacent multiply connected surface segments extending around said multiply connected surface, with each of the segments being defined by a first node at which one of said first and second insulated conductor means changes from the first to the second helical pitch sense, and a second node at which the other of said first and second insulated conductor means changes from the second to the first helical pitch sense; wherein said first signal terminal is electrically connected to the first nodes at a first substantially common point; and wherein said second signal terminal is electrically connected to the second nodes at a second substantially common point.

29. The electromagnetic antenna of claim **28** wherein said multiply connected surface is a surface of a toroidal form having a major axis; and wherein the first and second substantially common points are located generally along the major axis of the toroid form.

30. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a spherical surface;

first insulated conductor means extending in a first conductive path around and at least partially over said spherical surface with at least a first winding sense;

second insulated conductor means exuding in a second conductive path around and at least partially over said spherical surface with at least a second winding sense, which is opposite from the first winding sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said spherical surface; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means.

31. The electromagnetic antenna of claim **30** wherein said first insulated conductor means extends in the first conductive path around and over said spherical surface with the first winding sense from a first node to a second node; and wherein said second insulated conductor means extends in the second conductive path around and over said spherical surface with the second winding sense from the second node to the first node in order that the first and second conductive paths are contrawound relative to each other and form a single endless conductive path around and over said spherical surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

32. The electromagnetic antenna of claim **30** wherein said first insulated conductor means extends in the first conductive path around and over said spherical surface with the first winding sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second conductive path around and over said spherical surface with the second winding sense from the third node to a fourth node and from the fourth node to the first node in order that the first and second conductive paths are contrawound relative to each other and form a single endless conductive path around and over said spherical surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

33. The electromagnetic antenna of claim **30** wherein said first insulated conductor means extends in the first conductive path around and partially over said spherical surface with the first winding sense from a first node to a second node, and also extends in a third conductive path around and partially over said spherical surface with the second winding sense from the second node to the first node in order that the first and third conductive paths form a first endless conductive path around and over said spherical surface; and wherein said second insulated conductor means extends in the second conductive path around and partially over said spherical surface with the second winding sense from a third node to a fourth node, and also extends in a fourth conductive path around and partially over said spherical surface with the first winding sense from the fourth node to the third node in order that the third and fourth conductive paths form a second endless conductive path around and over said spherical surface, with the first and third conductive paths being contrawound relative to the second and fourth conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal terminal is electrically connected to the second node.

34. The electromagnetic antenna of claim **30** wherein said spherical surface has a pair of poles; and wherein the first and second conductive paths generally intersect at each of the poles.

35. The electromagnetic antenna of claim **30** wherein said spherical surface has a pair of poles; and wherein the first and second conductive paths generally intersect away from each of the poles.

36. An electromagnetic antenna for use with an antenna signal, said electromagnetic antenna comprising:

a hemispherical surface;

first insulated conductor means extending in a first conductive path around and at least partially over said hemispherical surface with at least a first winding sense;

second insulated conductor means extending in a second conductive path around and at least partially over said hemispherical surface with at least a second winding sense, which is opposite from the first winding sense, in order that said first and second insulated conductor means are contrawound relative to each other around and at least partially over said hemispherical surface; and

first and second signal terminals respectively electrically connected to said first and second insulated conductor means.

37. The electromagnetic antenna of claim **36** wherein said first insulated conductor means extends in the first conductive path around and over said hemispherical surface with the first winding sense from a first node to a second node; and wherein said second insulated conductor means extends in the second conductive path around and over said hemispherical surface with the second winding sense from the second node to the first node in order that the first and second conductive paths are contrawound relative to each other and form a single endless conductive path around and over said hemispherical surface; and wherein said first and second signal terminals are respectively electrically connected to the first and second nodes.

38. The electromagnetic antenna of claim **36** wherein said first insulated conductor means extends in the first conductive path around and over said hemispherical surface with the first winding sense from a first node to a second node and from the second node to a third node; wherein said second insulated conductor means extends in the second conductive path around and over said hemispherical surface with the second winding sense from the third node to a fourth node and from the fourth node to the first node in order that the first and second conductive paths are contrawound relative to each other and form a single endless conductive path around and over said hemispherical surface; and wherein said first and second signal terminals are respectively electrically connected to the second and fourth nodes.

39. The electromagnetic antenna of claim **36** wherein said first insulated conductor means extends in the first conductive path around and partially over said hemispherical surface with the first winding sense from a first node to a second node, and also extends in a third conductive path around and partially over said hemispherical surface with the second winding sense from the second node to the first node in order that the first and third conductive paths form a first endless conductive path around and over said hemispherical surface; and wherein said second insulated conductor means extends in the second conductive path around and partially over said hemispherical surface with the second winding sense from a third node to a fourth node, and also extends in a fourth conductive path around and partially over said hemispherical surface with the first winding sense from the fourth node to the third node in order that the third and fourth conductive paths form a second endless conductive path around and over said hemispherical surface, with the first and third conductive paths being contrawound relative to the second and fourth conductive paths, respectively; wherein said first signal terminal is electrically connected to the first node; and wherein said second signal terminal is electrically connected to the second node.

40. The electromagnetic antenna of claim **36** wherein said hemispherical surface includes a planar surface associated with said first and second signal terminal.

41. The electromagnetic antenna of claim **40** wherein the planar surface is a ground plane.

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