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71 Applicant: **Corum, James f., Route 9, Box 207-B,
Morgantown West-Virginia 26505 (US)**

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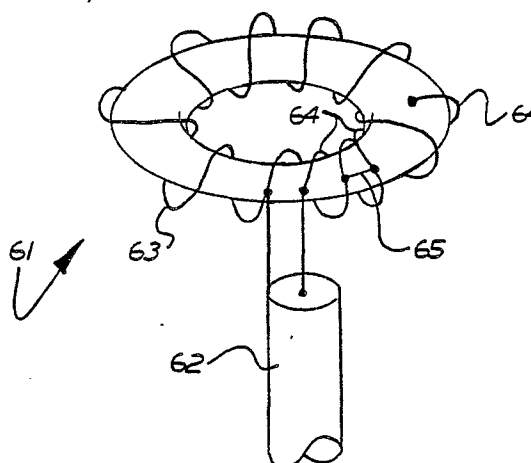
72 Inventor: **Corum, James F., Route 9 Box 207-B,
Morgantown West Virginia 26505 (US)**

84 Designated Contracting States: **DE FR GB**

74 Representative: **Wagner, Karl H., P.O.
Box 246 Gewuerzmuehlstrasse 5,
D-8000 München 22 (DE)**

54 **Antenna.**

57 An antenna for transmitting or receiving electromagnetic radiation, comprising a conductor configured to establish a closed standing wave path, and to inhibit the velocity of propagation and support a standing electromagnetic wave. An embodiment of the antenna shows a toroidal helix antenna (61), which is adapted for unbalanced feed from transmission line (62). A sliding tap (65) is moved to a point for proper impedance matching.



ANTENNABACKGROUND OF THE INVENTION

My invention relates to antennas used for either transmitting or receiving or both.

5 The main purpose of an antenna is to transmit electromagnetic energy into (or receive electromagnetic energy from) the surrounding space effectively. A transmitting antenna launches electromagnetic waves into space and a receiving antenna captures radiation, converting the electro-
10 magnetic field energy into an appropriate form (e.g. - a voltage to be fed to the input of a receiver).

 A transmitting antenna converts the radio frequency (RF) energy fed by a generator connected to its input into electromagnetic radiation. This radiation carries the
15 generator's energy away into space. The generator is giving up energy to a load impedance. As far as the generator is concerned, this load impedance may be replaced by a lumped element which merely dissipates the energy which the previous antenna radiated away.

20 The equivalent resistor, which would dissipate the same power as the antenna radiated away, is called the "antenna radiation resistance". In the real world, an antenna structure has losses (power dissipating mechanisms) due to the structure's finite conductivity, imperfect
25 insulation, moisture and physical environment. To the generator, these loss mechanisms absorb some of the power fed into the antenna structure, so that all of the input

power is not radiated away. The ratio of the radiated power to antenna structure input power is called the antenna efficiency. If the same current flows in the antenna radiation resistance, R_A , and in the antenna loss resistance R_L , then the efficiency in percent ($E_{\%}$) can be described by the simple equation

$$E_{\%} = \frac{R_A}{R_A + R_L} \times 100\%$$

Clearly, it is desirable to make the ratio R_A/R_L as great as possible (i.e., the antenna would be 100% efficient if R_L could be reduced to zero).

The particular application for which an antenna is to be used, along with certain physical laws and practical considerations primarily determines the type of antenna structure employed. Frequency f , wavelength λ , and velocity of propagation for electromagnetic waves v_p are related by the simple formula $\lambda = v_p/f$. At low and medium frequencies it may be economically unfeasible to construct an antenna radiating system whose physical dimensions are an appreciable portion of a free space wavelength. Typical vertical antennas must be on the order of one-eighth to one-quarter of a free space wavelength high in order to have R_A large enough to be considered as efficient antennas -- unless extensive measures are taken to make R_L negligible. At very low frequencies (e.g., $f = 15$ KHz) even a structure 1,000 feet high must be accompanied by a substantial engineering effort to make R_L small, in order to be considered as a "practical" transmitting antenna. One might ask, "Why not construct long horizontal antennas at these low frequencies, in order to raise the antenna radiation resistance?" Vertical antennas produce vertically polarized waves (i.e., waves for which an electric field intensity is perpendicular to the ground), whereas a horizontal wire produces a wave for which the electric

field intensity is parallel to the ground (horizontal polarization). A physical result following from the properties of wave propagation is that horizontally polarized waves propagating along the surface of the earth attenuate more rapidly than vertically polarized waves. Thus, for situations where ground wave propagation is to be employed, or for low frequency radiation, a vertically polarized antenna structure is often the most desirable or only acceptable solution (in spite of the physical and economical disadvantages). The single vertical radiator has another feature which is often desirable. It is omnidirectional in the horizontal plane - that is, equal amounts of vertically polarized radiation are sent out in all directions on the horizontal plane.

Sometimes a particular geographical region is to be served by a transmitting station. In this case, an array of towers or antenna elements spaced an appreciable portion of a wavelength may be used to direct the radiation. The resultant physical distribution of the electric field intensity in space is called the antenna pattern. As a consequence of an antenna system concentrating its pattern in a given direction, the received field strength is greater in that direction than when the antenna radiates into all directions. One may define a figure of merit for antennas which characterizes this property; antenna gain is defined as the ratio of the maximum field intensity produced by a given antenna to the maximum field intensity produced by a reference antenna with the same power input.

An additional antenna property is antenna resonance. When a given antenna structure is excited by a generator at a given frequency, the voltage and current at the antenna terminals are complex quantities; that is, they have real and imaginary mathematical components. The ratio of the complex voltage to the complex current at the terminals is called the antenna input impedance. As the generator frequency is varied (or alternatively, if the

generator frequency is fixed and the antenna dimensions are varied) there will be a particular frequency (or antenna dimension) for which the voltage and current are in phase. At this frequency the impedance will be purely resistive and the antenna is said to be resonant. A resonant antenna structure is one which will support a standing wave current distribution which has an integral number of nodes.

An antenna will radiate at any frequency for which it will accept power. However, the advantage of having a resonant antenna structure is that it is easier to match to the generator for efficient power transfer. This means that the system losses can be decreased and, hence, the overall system efficiency is increased at resonance. However, a vertical tower, for example, is not self-resonant unless it is electrically one quarter wavelength tall. At a frequency of 550 KHz (the low end of the AM broadcast band) a self-resonant tower must be about 447 feet tall. At 15 KHz it would have to be 16,405 feet tall!

The major problem associated with the types of antennas discussed so far is that the physical size (and cost) required for a given antenna efficiency becomes prohibitive as frequency is decreased (wavelength is increased). Furthermore, even in the ultra high frequency range (ultra short wavelengths) it is difficult to construct an electrically small antenna which is an efficient radiator. It would often be desirable, at any frequency in the electromagnetic spectrum, to be able to construct a small antenna whose physical dimensions are much less than a wavelength, whose radiation efficiency is high, and one which is capable of producing a specified polarization or polarization mixture. For example, it would be desirable to produce vertical polarization at low frequencies, or circular polarization for VHF FM broadcasting, etc.

In addition to the antennas discussed so far, there are other antenna configurations and circuit elements which should not be confused with my invention. My

invention is not a toroidal inductor. A perfect toroidal inductor has zero radiation efficiency, and so is not an antenna at all. My invention is not what is commonly termed "the small loop antenna", which produces the well-known azimuthally directed (horizontal) electric field with a $\sin \theta$ pattern, where θ is the angle of from the spherical coordinate polar axis, where the loop lies in the azimuthal plane. My invention is not what is commonly called a "normal mode helix"; which is a solenoidally wound structure, having a distinct beginning and ending to the helix. My invention is not what is commonly called the "multiturn loop antenna", which has multiple windings which either lie in the azimuthal plane or are coiled along the loop's axis of symmetry.

It is helpful to understanding my antenna to first present some approximate analytical considerations for certain prior art antennas.

The Normal Mode Helix

A solenoidally wound coil or helix is shown in Figure 1(a). By assuming the antenna current to be uniform in magnitude and constant in phase over the entire length of the helix, Kraus has shown that a normal mode helix (one whose dimensions are much less than a free space wavelength and that radiates normal to the solenoid axis) may be decomposed into a single small loop as in Figure 1(b) plus a single short dipole as in Figure 1(c). See John D. Kraus, Antennas (McGraw Hill Book Co. 1950), especially the portions beginning at pages 157, 160, and 179, which is incorporated herein. Kraus's analysis assumes that the current is uniform over the entire helix and is of the form $I_0 e^{j\omega t}$. The fields of a loop and short dipole for such excitation are well known and are given in polar coordinates (r, θ, ϕ) , using standard vector terminology, by

Loop:

$$(1) \quad \bar{E} = E_{\phi} \hat{\phi} = \frac{120\pi^3 b^2 I_o}{r\lambda^2} \sin\theta e^{j\omega t} \hat{\phi}$$

Short dipole:

$$(2) \quad \bar{E} = E_{\theta} \hat{\theta} = \frac{j60\pi I_o s}{r\lambda} \sin\theta e^{j\omega t} \hat{\theta}$$

5

where b = the radius of each turn of the helix

s = the turn-to-turn spacing of the helix

By the principle of linear superposition, the fields for the normal mode helix immediately follow as:

$$(3) \quad \bar{E} = E_{\theta} \hat{\theta} + E_{\phi} \hat{\phi}$$

10 Equation (1) may be directly obtained by assuming a uniform time varying flow of electric charges (an electric current) along the circumference of the loop.

There is an alternative way to derive Equation (1) which proceeds from the introduction of a fictitious conceptual aid. This very useful tool is a great assistance to performing field computations for helices and solenoids. 15 Kraus has shown that a loop of electric current, i.e., -- electric charges flowing around the circumference of a loop, produces the same radiation fields as those of a flow of fictitious magnetic charges moving up and down the axis of 20 the loop. The fields external to a helically wound solenoid can be found by assuming a flow of electric charges around the helix, or by assuming a flow of fictitious magnetic charges moving along the axis of the solenoid. 25 The latter computation is much simpler to perform analytically than the former.

One quickly notices from Equations (1) and (2) that the $\hat{\theta}$ and $\hat{\phi}$ components are in phase quadrature (note: $j = e^{j\pi/2}$), that is, they are 90° out of phase.

This causes the radiation zone $\vec{E}$ field at a point to rotate in time and in the resultant polarization is said to be elliptically polarized with an axial ratio given by:

$$(4) \quad AR \triangleq \frac{|E_{\theta}|}{|E_{\phi}|}$$

- 5 Figure 2 shows the different types of polarization obtainable from a normal mode helix. Figure 2(a) is the general case of elliptical polarization. Figure 2(b) shows the case of vertical polarization, such as produced when $b=0$, that is, when the helix is reduced to a dipole. Figure 2(c) shows
10 horizontal polarization, such as produced when $s=0$, that is, when the helix is reduced to a loop. Figure 2(d) shows the circular polarization, such as when $E_{\theta} = E_{\phi}$.

Propagation Effects on a Helix

- The velocity of propagation of electromagnetic
15 disturbances in free space is the speed of light. Electromagnetic waves propagate along a wire with a speed somewhat less than, but very close to the speed of light in free space. However, an electromagnetic wave propagating along a solenoid or helix, such as Figure 3, will travel
20 with a velocity of propagation (v_p) considerably less than the speed of light (c). One can write this as

$$(5) \quad v_p = V_f c$$

- where V_f is called the velocity factor. In free space $V_f = 1$. On a copper wire $V_f \approx .999$. On a helical delay
25 line V_f may be on the order of $1/10$ or $1/2$. (Intuition indicates that the wave traveling along the spiral helix has to travel further than a wave that could travel in free space parallel to the solenoid's axis and therefore V_f should be less than unity - but this is only part of

the story.) What this leads to is that a helix may have a physical length less than a free space wavelength (λ_o , where $\lambda_o = c/f$), while it is still electrically one wavelength. Calling the electrical wavelength on the helix the guide wavelength λ_g one sees that:

$$(6) \quad \lambda_g = \frac{v_p}{f} = V_f \lambda_o$$

This means that one can make a helix behave electrically equivalent to a free space wavelength long while it is physically V_f times smaller. Kandoian and Sichak have determined an expression for V_f on a helix as in Figure 3 in the form:

$$(7) \quad V_f = \frac{1}{[1+20(2b\frac{N}{\ell})^{2.5} (2b/\lambda_o)^{1/2}]^{1/2}}$$

where b = radius of each turn of the helix

$\lambda_o = c/f$ (measured in the same units as the radius b)

ℓ = length of the helix

N = number of turns

See Reference Data for Radio Engineers (Howard & W. Sams & Co., Inc., 1972) pages 25-11 to 25-13, which is incorporated by reference. Equation (7) assumes that $4nb^2/\lambda_o < 1/5$, where $n = N/\ell$.

SUMMARY OF THE INVENTION

An important feature of the antennas in my invention is that even though they can have a much smaller physical size than prior antennas, they can transmit or receive electromagnetic waves with a very high antenna efficiency. Thus, the antennas of the invention possess greater radiation resistance and radiation efficiency than loop antennas of similar size. Additionally, antennas according to the invention radiate controllable mixtures

of vertically, horizontally and elliptically polarized electromagnetic waves and possess radiation power patterns different from those produced by small loop antennas.

Antennas according to preferred embodiments of the invention are configured to behave as slow wave devices. The antennas are configured to establish a closed, standing wave path. The conductor configuration and the path established thereby inhibit the velocity of propagation of electromagnetic waves, and the path supports the standing wave at a pre-selected frequency. The preferred embodiments of the invention described herein include various arrangements of conductors arranged in loop configurations; but the conductor or conductors are configured so that they are not arranged in simple circles, and rather are wound about real or imaginary support forms to increase the length of the physical path of the conductor while maintaining a relatively compact antenna. The path in each case is configured to inhibit the velocity of the electromagnetic wave and to support a standing wave at a pre-selected frequency.

An antenna according to one such embodiment comprises an electrical conductor configured with multiple, progressive windings in a closed or substantially closed geometrical shape. This shape can be established by a physical support form or it can be a geometrical location as where the antenna has self-supporting conductors. Such a shape can be topologically termed a "multiply connected geometry"; for example, a conductor can be in the form of more than one winding in a geometrically closed configuration or multiply connected geometry. The cross-section of this configuration can be circular (as where the configuration is a toroidal helix), or it can have the general form of an ellipse, a polygon, or other shapes not generally circular in cross-section; the configuration can be symmetrical or assymmetrical, polygonal, and it can be essentially two dimensional or configured in three dimensions.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1(a)-1(c) are vector decompositions of several basic types of antennas (prior art).

5 Figs. 2(a)-2(d) are vector representations of polarizations produced by a helical antenna.

Fig. 3 is a schematic of a spirally wound antenna (prior art).

10 Fig. 4 is a schematic of a helically wound toroidal antenna according to the invention.

Figs. 5(a)-5(c) are isometric, top and side views of an antenna of the type in Fig. 4.

Fig. 6 is an isometric representation of a continuously wound, toroidal helical antenna according to the invention.

15 Fig. 7 is a vector representation showing the geometry for a circular loop antenna of nonuniform current.

20 Figs. 8 and 9 show azimuthal plane radiation field patterns for a resonant toroidal loop antenna according to the invention with current flow in opposite directions, and Fig. 10 shows the effect of superimposing the patterns of Figs. 8 and 9.

25 Fig. 11 shows an azimuthal plane radiation pattern for an antenna of the type which produced the field illustrated in Fig. 8 but which has in effect been flipped over, and Fig. 12 shows the effect of superimposing the patterns of Figs. 8 and 11.

Fig. 13 is a bottom view of a multiply-wound helical antenna.

30 Fig. 14 illustrates in schematic form the RMS field pattern of an omnidirectional vertically polarized antenna element according to the invention.

In Fig. 15, a quadrifilarly wound toroidal helical antenna according to the invention is shown in perspective.

35 Fig. 16 shows the RMS field pattern produced by

a toroidal loop antenna of the type producing the pattern of Fig. 8, but with its feed point rotated 90° from the antenna to which Fig. 8 relates.

5 Fig. 17 is an isometric view of another embodiment of the invention including parasitic array construction.

Fig. 18 is a perspective view of a parasitic array antenna according to the invention, composed of toroidal loops.

10 Fig. 19 is a graphical representation of the resistance and reactance characteristics vs. frequency for an antenna of the type shown in Fig. 5.

Figs. 20 and 21 are VSWR curves for an HF toroidal loop antenna according to the invention for two separate resonance values.

15 Fig. 22 is a graph of curves of input impedance vs. frequency for two variations of a toroidal loop antenna of the type shown in Fig. 13.

Fig. 23 is another embodiment of the invention comprising an HF rectangular toroidal loop antenna.

20 Fig. 24 is a graph of resistance and reactance vs. frequency curves for the antenna of Fig. 23.

Figs. 25(a) and (b) show prior art forms of contrawound helix circuits.

25 Figs. 26(a) and (b) illustrate the current paths on the circuits of Figs. 25(a) and (b).

Fig. 27 shows an antenna according to my invention comprising a contrawound helical torus for producing vertical polarization.

30 Figs. 29-33 are isometric views of other antenna constructions according to the invention.

Fig. 34 depicts an antenna configuration not within the scope of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 4 shows an antenna 41 which is an embodiment of my invention. An electrical conductor 42 which can be, for example, an elongated conductor such as a length of conducting tape, wire or tubing is helically wound about a non-conducting toroidally shaped support 43. The turn-to-turn spacing "s" between each winding is uniform. The dimension "b" is the radius of each winding and 2b may be termed the "minor diameter" of the antenna. The dimension "a" is the radius of the circle which comprises the center-line axis 44 of the toroid. Another useful parameter is "N" which is the number of turns. If the toroidal helix of Figure 4 is considered to be the helix of Figure 3 bent around into a toroid, one notes that $\ell = 2\pi a$ and $N = \frac{2\pi a}{s}$. Equation (7) becomes,

$$(7a) \quad V_f = \frac{1}{[1+20(\frac{2b}{s})^{2.5} (2b/\lambda_0)^{1/2}]^{1/2}}$$

Figures 5(a), 5(b), 5(c) show an antenna 51 similar to antenna 41, but adapted to balanced feed. The helically wound conductor 52 is not continuous, but rather has two ends 52a, 52b which are used as the feed point taps for the antenna. Preferably, these ends 52a, 52b are as close to each other as possible without electrically interfering with each other. These ends 52a, 52b should be near each other, that is, the ends should be near enough that the electromagnetic waves on the antenna follow a closed path.

Figure 6 shows another toroidal helix antenna 61, which is adapted for unbalanced feed from an unbalanced transmission line 62. The conductor 63 is continuous. In addition, there is a shorter conductor 64 helically wound around the toroidal support between some of the turns of the continuous conductor 63. A sliding tap 65 connects the two conductors 63, 64. One side of the transmission line is connected to one end of the shorter conductor 64 and the

other side is attached to the continuous conductor 63. The sliding tap 65 is moved to a point for proper impedance matching. This point is found empirically by actually testing the antenna at the chosen frequency and moving the sliding tap 65 to the optimum position.

Before describing more complicated toroidal loop embodiments, it is useful to present an approximate mathematical analysis of the toroidal loop antenna embodiments of my invention.

As has already been discussed, helical structures possess the property that electromagnetic waves propagating on them travel with velocities much less than waves propagating in free space or on wires. By properly choosing the helix diameter and pitch, one can control the velocity of propagation in a manner well known in the science of transmission line engineering. Since the velocity of propagation for these traveling waves on helical structures is much less than that of waves traveling in free space, the wavelength λ_G of a wave on the helix will be much less than the wavelength λ_0 for a wave traveling in free space at the same frequency. By bending the helix into the form of a torus, one is able to excite a standing wave for which the circumference C is one wavelength. The physical dimension of the circumference can be calculated from the equations for velocity of propagation on slow wave structures.

It is useful to note that electric charges traveling along the helix produce the same fields that "magnetic charges" (if they existed) would produce if they were traveling along the axis of the helix. Consequently, our toroidal helix has the same fields that a loop oscillating magnetic charges would produce. This is very helpful in the mathematical analysis of our toroidal loop antenna and is based upon the principle of duality.

The slow wave feature of helices which is employed in the toroidal loop antennas of my invention permits the construction of a resonant structure whose circumference is much less than a free space wavelength, but whose

electrical circumference is nevertheless electrically a full wavelength. Such a structure is resonant. At this point it is appropriate to mention categories or types of antennas:

- 5 1. Electric dipoles. These are straight wires upon which electrical charges flow. AM broadcasting towers are a typical example of this type of antenna. A vertical electric dipole will produce a vertically polarized radiation field.
- 10
2. Magnetic dipoles. These are linear structures upon which "magnetic charges" flow. They have radiation fields which are the duals to those of the electric dipoles. (That is, their magnetic field patterns are the same as the electric dipoles' electric field patterns.) A typical example of this antenna is the Normal Mode Helix antenna, already mentioned above in the Background of the Invention.
- 15
3. Electric Loops. These are closed loop structures (perhaps having several turns) in which electric currents flow. They have the same patterns as magnetic dipoles and may be regarded as a magnetic dipole whose axis coincides with that of the loop. Typical examples are the loop antennas used for radio direction finding and for AM broadcast receivers. A flat loop will produce a horizontally polarized radiation field.
- 20
4. Magnetic loop antennas. These would be closed loops of flowing magnetic current. They would have the same field patterns as electric dipoles. Indeed a horizontal magnetic loop would have the same radiation pattern as a vertical tower or whip antenna.
- 25
- 30
- 35

Prior to the invention of my toroidal loop antenna, the typical way magnetic loop antennas could be made was to excite a circular slot in a large ground plane. The ground plane had to be many wavelengths in extent and the annular slot, in order to resonate, had to have a mean circumference equal to a free space wavelength.

Because of the helical winding, the toroidal loop embodiments of my invention behave as the superposition of a loop of magnetic current and a loop of electric current. The electric loop component generates a horizontally polarized radiation field, and the magnetic loop component generates a vertically polarized radiation field. By varying the helix distribution, one can control the polarization state of the radiation field.

It was explained in the Background of the Invention that there has been a mathematical analysis of the helical antenna by Kraus, and Kandoian and Sichak. The helically wound toroidal antenna embodiment of my invention can be analyzed by taking the linear helix discussed above and bending it around into a torus and exciting it with a high frequency signal generator. Since the guide wavelength is much smaller than λ_0 , one can make a torus with even a small circumference behave electrically as a complete wavelength (that is, $C = 2\pi a = \lambda_g \ll \lambda_0$), or multiples of a wavelength. One now has a resonant antenna whose properties (input impedance, polarization, radiation pattern, etc.) are distinctly different from the linear normal mode helix discussed above. For example, one could not analyze this new structure by assuming that the current is uniformly distributed in amplitude and phase along the circumference. (Unless of course, the torus were very, very small). However, there are certain features of the normal mode helix analysis that one can use as an aid to understanding the toroidal loop antenna.

Assume that the current distribution is non-uniformly distributed along the azimuthal angle ϕ . Also assume that the helix can be decomposed into a continuous loop of (sinusoidally distributed) electric current plus a continuous loop of (sinusoidally distributed) magnetic current. The radiation properties can then be ascertained by employing the principle of superposition. The following discussion proceeds through these separate computations and combines them to determine the toroidal loop's radiation properties.

Radiation Fields Produced by a Large Loop of Electric Current

We consider an electric current of the form $I_\phi(\phi') = I_0 \cos n\phi' e^{j\omega t}$ excited upon a circular wire loop of radius a . It should be noted that this uses a standing wave with n nodes; that is, the analysis is of the n^{th} harmonic where $n = 0, 1, 2, \dots$. In other words, the circumference of the loop is n guide wavelengths: $C = n\lambda_g$. Figure 7 shows the geometry for a circular loop of non-uniform current used in the following analysis of the electromagnetic fields $\vec{E}$ and $\vec{H}$ in the radiation zone far from the antenna. The source density may be written as

$$(8) \quad \vec{J}(\vec{r}') = I_0 \cos n\phi' e^{j\omega t} \delta(\cos\theta') \frac{\delta(r'-a)}{a} \hat{\phi}.$$

In the far field (radiation zone) $r \gg a$, and the position vectors $\vec{r}'$ of all the elements of the ring $d\vec{l}$ may be regarded as parallel. This yields:

$$(9) \quad r = R - a \cos \psi.$$

It has been shown that

$$(10) \quad \vec{R} \cdot \vec{r}' = \cos \psi = \sin\theta \sin\theta' \cos(\phi - \phi') + \cos\theta \cos\theta'.$$

See E.A., Wolff, Antenna Analysis (John Wiley Book Co. 1966) at page 111. Since $\theta' = \pi/2$ one has:

$$(11) \quad r = R - a \sin\theta \cos(\phi' - \phi).$$

5 An element of the ring of current has an electric dipole moment

$$(12) \quad d\bar{p} = p d\bar{\ell}$$

where P is the electric dipole moment per unit length of the wire. The electric and magnetic fields are related to the potentials as

$$10 \quad (13) \quad \bar{H} = \frac{1}{\mu} \nabla \times \bar{A}$$

where μ is the permeability of space, and $\bar{A}$ is a vector potential,

$$(14) \quad \bar{E} = -j\omega\bar{A} - \nabla V$$

15 where V is a scalar potential, and in the radiation zone,

$$(15) \quad \bar{E} = Z_0 \bar{H} \times \hat{R}$$

where Z_0 is the characteristic impedance of free space. Now

$$(16) \quad d\bar{A} = \frac{\mu_0 \bar{J}(\bar{r}) e^{j\beta r}}{4\pi r}$$

20 where β is the phase constant $\frac{2\pi}{\lambda}$ and μ_0 is the permeability of free space.
so that

$$(17) \quad d\bar{A} = \frac{\mu_0}{4\pi r} e^{-j\beta r} (-j\omega d\bar{p})$$

Equation (13) now leads to

$$(18) \quad d\bar{H} = \frac{-\omega\beta}{4\pi r} e^{-j\beta r} d\bar{p} \times \hat{R}$$

5 Collecting together Equations (8), (12) and (18) one has the incremental magnetic field intensity vector

$$(19) \quad d\bar{H} = \frac{j\beta a I_0}{4\pi r} e^{j[\omega t - \beta R + \beta a \sin\theta \cos(\phi' - \phi)]} \cos n\phi' [\cos(\phi - \phi')\hat{\theta} + \cos\theta \sin(\phi' - \phi)\hat{\phi}] d\phi$$

10 In the denominator of this last equation there are neglected quantities of the order of a in comparison with R . This cannot be done in the exponential terms since βa is not small with respect to the other exponential terms and has an important effect in the phase. The magnetic field intensity can now be found by direct integration:

$$(20) \quad H_\theta = \frac{j\beta a I_0}{4\pi R} e^{j(\omega t - \beta R)} \int_{-\pi}^{\pi} \cos(\phi' - \phi) \cos n\phi' e^{j\beta a \sin\theta \cos(\phi' - \phi)} d\phi$$

15

One can obtain an expression for H_ϕ from that of H_θ simply by replacing $\cos(\phi' - \phi)$ by $\sin(\phi' - \phi)$ in the integrand. Let $\rho = \phi' - \phi$. Then

$$(21) \quad \cos n\phi' = \cos n\phi \cos n\rho - \sin n\phi \sin n\rho$$

20 This gives

$$(22) \quad H_\theta = \frac{-j\beta a I_0}{4\pi R} e^{j(\omega t - \beta R)} \left[-\sin n\phi \int_{-\pi}^{\pi} \cos \rho \sin n\rho e^{j\beta a \sin\theta \cos \rho} d\rho + \cos n\phi \int_{-\pi}^{\pi} \cos \rho \cos n\rho e^{j\beta a \sin\theta \cos \rho} d\rho \right]$$

The first integral will vanish because the integrand is odd. The second integral has an even integrand so that the limits may be transformed to 0, π and the integral itself expressed in terms of the derivative of a Bessel Function:

$$5 \quad (23) \quad \frac{dJ_n(x)}{dx} = J'_n(x) = j \frac{e^{-j\pi/2}}{\pi} \int_0^\pi \cos\phi \cos n\phi e^{jx\cos\phi} d\phi$$

where $x = \beta a \sin\theta$.

Thus one is led to a θ component of the magnetic field intensity of the form

$$(24) \quad H_\theta(R) = \frac{E_\phi(R)}{Z_0} = \frac{-\beta a I_0}{2R} \cos n\theta J'_n(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

10 where the circumference of the loop is $n\lambda_g$. The expression for H_ϕ may be found, as stated above, by simply replacing $\cos(\phi' - \phi)$ by $\sin(\phi' - \phi)$ in the integrand. Then

$$(25) \quad H_\phi = \frac{-j\beta a I_0}{4\pi R} \cos\theta e^{j(\omega t - \beta R)} \int_{-\pi}^\pi \sin(\phi' - \phi) \cos\phi' e^{j\beta a \sin\theta \cos(\phi' - \phi)} d\phi.$$

15 Again let $\rho = \phi' - \phi$ and use the trigonometric identity, Equation 21, to obtain

$$(26) \quad H_\phi = \frac{-j\beta a I_0}{4\pi R} \cos\theta e^{j(\omega t - \beta R)} \left[\cos n\phi \int_{-\pi}^\pi \cos n\rho \sin\rho e^{j\beta a \sin\theta \cos\rho} d\rho - \sin n\phi \int_{-\pi}^\pi \sin n\rho \sin\rho e^{j\beta a \sin\theta \cos\rho} d\rho \right]$$

Now

$$(27a) \cos n\phi \sin\phi = \frac{1}{2}[\sin(n+1)\phi - \sin(n-1)\phi]$$

$$(27b) \sin n\phi \sin\phi = \frac{1}{2}[\cos(n-1)\phi - \cos(n+1)\phi]$$

so that

$$(28) \int_{-\pi}^{\pi} \cos n\phi \sin\phi e^{j\beta a \sin\theta \cos\phi} d\phi = 0$$

5 and

$$(29) \int_{-\pi}^{\pi} \sin n\phi \sin\phi e^{j\beta a \sin\theta \cos\phi} d\phi = j^{n-1} \pi J_{n-1}(x) - j^{n+1} \pi J_{n+1}(x)$$

where one lets $x = \beta a \sin\theta$, and using the relation

$$(30) \int_0^{\pi} e^{jx \cos\phi} \cos n\phi d\phi = j^n \pi J_n(x).$$

10 Thus, Equation (26) becomes

$$(31) H_{\phi} = \frac{-j\beta a I_0}{4R} \cos\theta e^{j(\omega t - \beta R)} j^{n+1} [J_{n+1}(x) + J_{n-1}(x)] (-\sin n\phi).$$

Now, the recursive relation for the Bessel Functions can be written as

$$(32) J_{n-1}(x) + J_{n+1}(x) = \frac{2n}{x} J_n(x)$$

15 so that one can finally collect Equation (24) into the expression

$$(33) H_{\phi} = \frac{-E_{\theta}}{Z_0} = \frac{-\beta a I_0 n}{2R} \sin n\phi \frac{-J_n(\beta a \sin\theta)}{\beta a \tan\theta} e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

Equations (24) and (33) must now be substituted back into

Equation (3). One then has the total electric field intensity vector for a single loop of electric current:

$$(3) \quad \vec{E} = E_{\theta} \hat{\theta} + E_{\phi} \hat{\phi}$$

and

$$5 \quad (34) \quad \vec{H} = H_{\theta} \hat{\theta} + H_{\phi} \hat{\phi}$$

At this point one still does not have the radiation fields of the toroidal loop antenna. Before these can be found, one must also compute the fields produced by a large loop of magnetic current.

10 Radiation Fields Produced by a Large Loop of Magnetic Current

Consider a circular loop of sinusoidally distributed magnetic current. Suppose a standing wave of magnetic current of the form

$$I_{\phi}^m(\phi') = I_m \sin(n\phi' + \alpha) e^{j\omega t}$$

15 excited on a circular magnetically conducting loop. (This is really the toroidal flow of electric charge.) For convenience, we let $\alpha = 0$ and choose the electric and magnetic currents to be in phase quadrature. The source density is again of the form

$$20 \quad (35) \quad \vec{J}_m(\vec{r}') = I_m \sin n\phi' e^{j\omega t} \int (\cos\theta') \frac{\delta(r'-a)}{a} \hat{\phi} .$$

An element of the ring of magnetic current has a magnetic dipole moment

$$(36) \quad d\vec{P}_m = P_m d\vec{\ell}$$

where P_m is the magnetic dipole moment per unit length of the

source. From Maxwell's equations we have

$$(37) \quad \vec{E} = \frac{1}{\epsilon} \nabla \times \vec{F}$$

where ϵ is the permeability of the medium.

$$(38) \quad \vec{H} = -j\omega\vec{F}$$

5 where $\vec{F}$ is the electric vector potential. This time

$$(39) \quad d\vec{F} = \frac{\epsilon J_m e^{-j\beta r}}{4\pi r}$$

which can be written as

$$(40) \quad d\vec{F} = \frac{\epsilon}{4r} e^{-j\beta r} (-j\omega d\vec{P}_m)$$

whence

$$10 \quad (41) \quad d\vec{E} = \frac{-\omega\beta}{4\pi r} d\vec{P}_m \times \hat{R}.$$

One writes this out explicitly as

$$(42) \quad d\vec{E} = \frac{-j\beta a I_m}{4\pi R} e^{j[\omega t - \beta R + \beta a \sin\theta \cos(\phi' - \phi)]} \\ \sin n\phi' [\cos(\phi' - \phi)\hat{\theta} + \cos\theta \sin(\phi' - \phi)\hat{\phi}] d\phi'$$

This is readily integrated, as before, to give

$$15 \quad (43) \quad E_\theta = Z_0 H_\phi = \frac{-\beta a I_m}{2R} \sin n\phi J'_n(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

and

$$(44) \quad E_\phi = -Z_0 H_\theta = \frac{-n\beta a I_m}{2R} \cos n\phi \frac{J_n(\beta a \sin\theta)}{\beta a \tan\theta} e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

Now, call the magnetically produced electric fields $\vec{E}^m$ and

the electrically produced electric fields $\bar{E}^e$. Then, employing the full symmetry of Maxwell's Equations one writes

$$(45) \quad \bar{E} = \bar{E}^e + \bar{E}^m$$

$$5 \quad (46) \quad \bar{H} = \bar{H}^e + \bar{H}^m$$

where

$$(47) \quad \bar{E}^e = E_{\theta}^e \hat{\theta} + E_{\phi}^e \hat{\phi}$$

and

$$(48) \quad \bar{E}^m = E_{\theta}^m \hat{\theta} + E_{\phi}^m \hat{\phi}$$

10 By the way, the equivalent (fictitious) magnetic current associated with the electric current I_0 flowing in a solenoid, such as in Figure 3, has a magnitude given by

$$(49) \quad I_m = \omega \mu \frac{\pi b^2}{s} I_e$$

where b = radius of the solenoid

15 s = turn to turn spacing of the solenoid.

See Kraus, Antennas, supra at page 158 (in this discussion l is replaced by s , and A by πa^2 , and there is chosen

$$I_m = \mu \frac{dq_m}{dt}.$$

20 This expression may be used in Equations (43) and (44). We are now in a position to determine the total radiation field and radiation resistance of the isolated toroidal loop antenna of my invention for the case where $\alpha = 0$.

Analysis of the Fields Produced by a Toroidal Loop Antenna

25 The analysis so far has prepared the way so that one can consider the toroidal helix to be composed of a

single resonant magnetic loop (due to an actual solenoidal flow of electric charge around the rim of the torus) plus a single resonant electric loop (due to the electric charge flowing along the turn-to-turn spacing of the helix). This is the basic assumption for the present analysis of the toroidal loop antenna. A more rigorous analysis could be made by assuming a spiral electric current around the helically wound torus. Such an analysis would require a great deal more effort but would probably be desirable for near field effects. However, the radiation zone effects should be consistent with this approximate analysis.

The radiation fields of the helically wound toroidal loop antenna are given by the linear superposition indicated in Equation (45) where the component fields are taken from Equations (24), (33), (43) and (44). These results are collected here for later reference.

$$(50a) \quad E_{\phi}^e = \frac{-\beta a Z_o I_o}{2R} \cos n\phi J_n'(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

$$(50b) \quad E_{\theta}^e = \frac{n\beta a Z_o I_o}{2R} \sin n\phi \frac{J_n(\beta a \sin\theta)}{\beta a \tan\theta} e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

$$(50c) \quad E_{\theta}^m = \frac{-\beta a I_m}{2R} \sin n\phi J_n'(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

$$(50d) \quad E_{\phi}^m = \frac{-n\beta a I_m}{2R} \cos n\phi \frac{J_n(\beta a \sin\theta)}{\beta a \tan\theta} e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

where

$$(51) \quad I_m = \omega \mu \frac{\pi b^2}{s} I_o$$

Note that if $n = 0$, the electric current is uniform around the loop and the magnetic current, Equation (35), vanishes. The radiation fields then reduce to the classical loop field of Equation (1).

$$(J_0'(x) = -J_1(x) \text{ and } J_1(x) \rightarrow \frac{x}{2}).$$

Of most interest is the resonant toroidal loop antenna. For this antenna $n = 1, 2, \dots$. One is particularly interested in the case for which $n = 1$ and in this case the fields of Equation (50) in the azimuthal plane reduce to

$$(52a) \quad E_{\phi} = \frac{-\beta a Z_0 I_0}{2R} J_1'(\beta a) \cos\phi$$

$$(52b) \quad E_{\theta} = \frac{-\beta a I_m}{2R} J_1'(\beta a) \sin\phi$$

These are sketched in Figure 8 for the case where $|I_m| = Z_0 I_0$, $I_{\phi}^e = \cos\phi$, and $I_{\phi}^m = \sin\phi$. If α were other than zero, the analysis could be repeated for that case. For example, if $\alpha = \pi/2$, I_m and I_e would be in phase and both E_{ϕ} and E_{θ} would vary as $\cos\phi$.

The Radiation Resistance Expression.

From Equation (50) one can compute the total average power radiated from the antenna from the Poynting integral

$$(53) \quad P_{avg} = \frac{1}{2} R e \left\{ \oint (\vec{E} \times \vec{H}^*) \cdot \hat{r} dA \right\}.$$

That is, for the case where $n = 1$, one may use Equation (50) and rewrite Equation (53) as

$$(54) \quad P_{avg} = \int_0^{2\pi} \int_0^{\pi} \frac{\pi E_{\phi}^2 + E_{\theta}^2}{2Z_0} R^2 \sin\theta \, d\theta d\phi$$

The average power delivered to a resistive load by a sinusoidal source is

$$(55) \quad P_{avg} = 1/2 I_0^2 R$$

Equating Equations (54) and (55) gives an expression for the radiation resistance as

$$(56) R_r = \int_0^{2\pi} \int_0^\pi \frac{E_\phi^2 + E_\theta^2}{Z_0} R^2 \sin\theta \, d\theta d\phi$$

This integral cannot be carried out in closed form and depends upon each loop geometry.

5 The following embodiments demonstrate how toroidal loop elements according to my invention, with the fields of equation 50, can be superposed to obtain various desired antenna patterns.

Bidirectional Horizontal Polarization

10 Recall that the antenna pattern of Figure 8 arose from the situation producing the fields of Equation 52. If we flip over this toroidal loop (on the x-y plane) and reverse the loop current, the antenna will have the radiation pattern shown in Figure 9. If we now superpose these two patterns, our new antenna will have the "figure eight" horizontally polarized pattern of Figure 10. The vertically
15 polarized components have cancelled one another. What has happened is that the magnetic currents, I_m , have cancelled one another leaving only the fields produced by the electric currents, I_e .

20 Bidirectional Vertical Polarization

Flipping over an antenna having the pattern of Figure 8 generates the radiation pattern of Figure 11. If we now superpose the antennas giving the patterns of Figure 8 and Figure 11, the resultant pattern will be the vertically
25 polarized antenna pattern of Figure 12. In this example, the electric currents have been phased out, and only the magnetic currents are left to produce the vertically polarized field in the azimuthal plane. One embodiment of this approach (and one for obtaining horizontal polarization)
30 is indicated in Figure 13, which is a bottom view of a multiply-wound helix. The bars BC and B'C' are for feeding

the toroidal loop and act as phasing lines. When fed at AA', the structure produces a vertically polarized field pattern in the plane of the torus. If B and B' or C and C' are interchanged, the azimuthal plane field pattern is horizontally polarized.

Omnidirectional Vertical Polarization

Quite often, an omnidirectional vertically polarized radiating element is desired. The previous embodiment demonstrates how an antenna constructed of two toroidal loops could produce a figure eight vertically polarized radiation field. If one now takes a second pair, that are also arranged to produce vertical polarization, and excited them and the previous pair with currents of equal magnitude but in phase quadrature (i.e., a 90 degree phase shift), the resultant field would be given by the expression

$$(65) E_{\theta} = \sin\phi \sin\omega t + \cos\phi \sin\omega t$$

which reduces to

$$(66) E_{\theta} = \sin(\theta + \omega t).$$

At any position, θ , the maximum amplitude of E_{θ} is unity at some instant during each cycle. The RMS field pattern is azimuthally symmetric as shown by the circle in Figure 14. The pattern rotates as a function of time, completing one revolution per RF cycle. So-called "turnstile antennas", that is, the use of multiple antennas with varying currents but with constant phase differences to obtain an antenna with omnidirectional coverage, are not new. See Kraus, Antennas, supra, at page 424 and G. H. Brown, "The Turnstile Antenna", Electronics, April, 1936. The embodiments of my invention now under discussion differ from the foregoing prior art by using toroidal loops instead of other elements.

Figure 15 shows an embodiment for implementing this method for obtaining omnidirectional vertical polarization. Figure 15(a) shows a quadrifilarly wound toroidal helix phased for producing omnidirectional vertical polarization (that is, perpendicular to the plane of the torus). This configuration is obtained by superimposing two bifilar helices, each of the type shown in Figure 13, and feeding them in phase quadrature. Figure 15(b) shows schematically the feed distribution for the antenna of Figure 15(a).

Omnidirectional horizontal polarization may be produced by feeding bidirectional horizontal polarization elements in an analagous manner.

Circular Polarization

Toroidal loops may be arranged so as to produce a circularly polarized radiation field. Consider the antenna pattern of Figure 8 produced by the basic toroidal loop. Suppose a second loop is constructed but with its current distribution (that is, the feed points) rotated by 90 degrees. The second toroidal loop produces the pattern shown in Figure 16. The superposition of these two patterns will produce circular polarization in the azimuthal plane if the two loops are excited in phase quadrature. Omnidirectional circular polarization can be produced by rotating the antennas producing the pattern of Figure 10 by 90 degrees and feeding them in phase quadrature with the antennas producing the pattern of Figure 12.

Operation at a Higher Order Mode

There is no reason why one should operate the toroidal loop only at a frequency where $n = 1$. One can also operate at a frequency where $n = 2$ and the "magnetic" current distribution varies as

(67) $I_{\phi}^m(\phi') = I_m \sin 2\phi'$

In this case, the fields are still given by Equation 50 and the radiation pattern will be more complex than the $n = 1$ mode. The disadvantage for using a higher order mode is that the antenna now will be physically larger. This is a disadvantage at low frequencies. However, at UHF this permits simpler construction and broader bandwidth.

Array Operation

In order to increase the gain or directivity for an antenna system one often employs multiple elements with some physical spacing. For example many AM broadcast stations employ an array of several vertical towers spaced some portion of the wavelength and directly excited with various amplitudes and phase shifted currents. Such antennas are called driven arrays.

Alternatively one may space tuned elements an appropriate portion of a wavelength from a single driven element and cause the tuned elements to be excited by the fields produced by the driven element. The fields from the driven element induce currents on these other elements, which have no direct electrical transmission line connection to a generator. Such elements are called parasitic elements, and the antenna system is called a parasitic array.

The toroidal loop may be employed in both the driven array and parasitic array configurations. The entire array, or only portions of it, may be constructed of toroidal loops. For example, in Figure 17 the driven element is a resonant linear element 1701 and the parasitic element is a tuned parasitically excited toroidal loop 1702. One could construct a driven array of several toroidal loops with various physical spacings and different amplitude and phased currents. These spacings may be concentric or linear depending upon the design criteria. Parasitic arrays

have been constructed entirely of toroidal loops as in Figure 18, which shows configuration for a typical two element toroidal loop parasitic array. The center toroidal loop 1801 is resonant at the frequency of interest and the parasitic element 1802 tuned as a director (resonated about 10% higher in frequency) and with a mean diameter about one-tenth of a wavelength greater than the mean diameter of the driven element for the given frequency of interest. These concentric configurations of Figures 17 and 18 measured gains typically on the order of 3 to 5 db over the center elements alone.

DESIGN EXAMPLES

A variety of toroidal loop configurations according to my invention can be constructed and typical resonant resistances can be varied (typically between a hundred ohms to several thousand ohms), depending upon the values a , b , and s and the order of the mode n excited on the loop as these terms were used in the equations herein. The variation of these parameters has also permitted a variety of polarization types and radiation patterns.

In the following constructions, it is assumed that one is using a driven toroidal loop radiating in its lowest order mode ($n=1$) with the radiation patterns of Figure 8. We could of course excited a higher order mode with a different n . The fields would still be given by Equation 50.

Example A - a conceptual elementary toroidal loop antenna for use with a home FM receiver.

A resonant frequency of 100 MHz ($\lambda_o = 3$ meters) and a torus' minor radius of $b = 1.27$ cm are arbitrarily chosen. If one winds the helix with turns spaced equal to b , then from Equation 7a we find $V_f = .296$. For lowest order resonance, the circumference $c = \lambda_g = V_f \lambda_o$. Thus we choose the major radius to be

$$(68) \quad a = \frac{V_f \lambda_o}{2\pi} = .141 \text{ meters (5.55 inches)}$$

In this example

$$(69) \quad I_m = \frac{\omega \mu \pi b^2}{s} I_o = 10.03 J_o$$

5 The fields can be determined from Equations 50 and they will be elliptically polarized with different axial ratios in different directions.

Example B - a conceptual toroidal loop for use at LF.

Suppose the desired operating frequency is 150 KHz.

10 ($\lambda_o = 2,000$ meters or 6,562 feet). One arbitrarily chooses the torus' minor radius as $b = 10$ feet (3.05 meters), and the turn-to-turn spacing as 2 feet (0.61 meters). From Equation 7a we find $V_f = .053$. Thus, for lowest order mode operation, the major radius is

$$(70) \quad a = \frac{V_f \lambda_o}{2\pi} = 17.02 \text{ m.} = 55.83 \text{ ft.}$$

15 In this example $I_m = 56.7 I_o$ and the fields follow from Equations 50. Notice that this antenna has a radius less than 1/10 wavelength and will be wound with 175 turns.

20 The following examples present experimental properties from several toroidal loop antennas according to my invention which have actually been constructed.

Example 1 = VHF Toroidal Loop

25 This antenna was wound with 70 turns of #16 gauge copper wire on a plastic torus of major radius $a = 6.25$ inches and minor radius $b = 1/2$ inch. The antenna was constructed as in Figure 5. The turn-to-turn spacing was $s = .56$ inch. This antenna was operated in the $n = 1$ mode (at 100 MHz). The predicted velocity factor was

$V_f(100 \text{ MHz}) = .336$. The measured velocity factor was
 $V_f(100 \text{ MHz}) = .332$. The measured feed point impedance
(which gives the characteristic resonance curves for $n = 1$)
is given in Figure 19.

5 Example 2 - VHF Vertically Polarized Toroidal Loop

The vertical polarization scheme of Figure 13 has
been built and measured. The physical construction parameters
were as follows: $a = 12.5$ inches, $b = .5$ inch, $s = .26$ inch.
The bifilarly wound loop was fed at AA'. The antenna had a
10 predicted $V_f = .153$ and a measured $V_f = .156$ at 46.0 MHz.
The ratio of vertical to horizontal polarization field
strength (or axial ratio) was 46. That is, the polariza-
tion produced was predominantly vertically polarized. These
measurements were made with a field strength meter and the
15 pattern indicated was that of Figure 12.

Example 3 - Omnidirectional VHF Array

The omnidirectional vertically polarized quadri-
filarly wound toroidal helix of Figure 15 was constructed on
a plastic torus. It had 64 quadrifilarly wound turns. The
20 physical parameters were $a = 4.0$ inches, $b = .3$ inch, $s =$
.4 inch. The structure resonated at 93.4 MHz and field
strength measurements indicated that it produced omni-
directional vertical polarization with an axial ratio of
76.4.

25 Example 4 - HF Toroidal Loop

An HF toroidal loop was constructed with 1,000
turns of #18 gauge wire wound with these physical parameters:
 $a = 2.74$ ft., $b = .925$ inches, $s = .2$ inch. The antenna's
VSWR was measured through a 4 to 1 balun transformer and
30 50 ohm coaxial cable. The VSWR curves are shown in

Figures 20 and 21 for two separate resonances of the antenna.

Example 5 - Medium Frequency Vertically Polarized Toroidal Loop

5 A 106 turn bifilar toroidal loop of the form of
Figure 13 was constructed with the following parameters:
a = 5.95 ft.; b = .95 ft., s = 4 inches. The turns were
measured at the feed point AA' and the results are shown in
Figure 22. The loop was constructed at a mean height of
10 3.5 ft. above soil with a measured conductivity of 2 milli-
mhos/meter. The graph shows two sets of curves. One set
of curves 2201 shows the feed point impedance vs. frequency
for the situation where 40 twenty foot long conducting ground
radials were symmetrically placed below the torus at ground
level. The second set of curves 2202 shows the same data for
15 the case where the ground radials have been removed. What
is interesting is that the conducting ground plane has very
little effect on the feed point impedance. This is to be
expected if the electric current tends to zero and the major
fields are produced by the magnetic current, I_m . However,
20 the proximity effect of the ground has not been analyzed
theoretically. It should be noted that the measured velocity
factor was $V_f = .094$ while the theoretical value is $V_f = .103$.
This corresponds to a difference of about 8.7%. This may be
due to the ground or it may be due to mutual coupling effects
25 on the bifilar windings. The theory which was developed
above was for an isolated single toroidal helix. It would
be applicable to multifilar helices if mutual effects are
neglectable.

Example 6 - HF Rectangular Toroidal Loop

30 An HF toroidal loop was constructed in a rectan-
gular shape with 116 equally spaced turns of #18 gauge wire
wound on a 2 1/2 inch (O.D.) plastic pipe form. The

rectangle was 27 inches by 27 inches and the feed point was at the center of one leg of the rectangle. See Figure 23. The feed point impedance was measured and is shown in Figure 24. The resonant frequency for this structure occurs where the reactive component of the impedance vanishes:
5 27.42 MHz.

Example 7 - Parasitic Array

A VHF parasitic array was constructed from a driven resonant quarter wavelength stub (above a 2 wavelength
10 diameter ground plane) and a parasitically excited toroidal loop, as in Figure 17. The loop had a major radius of $1/10$ wavelength and was tuned to resonate at a frequency 10% higher than the driven linear element. The measured gain over the driven element alone was 4 db. The array was
15 constructed at 450 MHz.

Example 8 - Contrawound VHF Toroidal Loop

A structure consisting of two helices wound in opposite directions at the same radius is called a contrawound helix. Slow wave devices have been constructed as
20 contrawound helices (operating as non-radiating transmission lines, or as elements in traveling wave tubes). See C.K. Birdsall and T.E. Everhart, "Modified Contrawound Helix Circuits for High Power Traveling Wave Tubes", Institute of Radio Engineers Transactions on Electron Devices, ED-3,
25 October, 1956, P. 190. See Figures 25a and 25b. I have constructed contrawound helices as in Figure 25b and pulled them into the form of a closed torus and operated them, not as transmission lines, but as resonant radiating toroidal helix antennas. The current paths on the contrawound helices
30 will cancel giving no resultant electric current propagating along the major circumference of the torus and a net angular electric current around the ring shaped minor

circumference of the helix. This is equivalent to a magnetic current around the major circumferences of the torus. Our previous analysis describes this mode of radiating toroidal helix if we let $I_0 = 0$ and $\alpha = \frac{\pi}{2}$. Then, the E^e of equations 50 vanish and the fields reduce to

$$(1) E_{\theta}^m = \frac{-\beta a I_m}{2R} \cos n\phi J'_n(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

$$(2) E_{\phi}^m = \frac{n\beta a I_m}{2R} \sin n\phi \frac{J_n(\beta a \sin\theta)}{\beta a \tan\theta} e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

The resultant radiation fields will be elliptically polarized. Such a device was fabricated (by bending the contrawound helix of Figure 25b wound into a torus) of 1/16" thick aluminum, with minor radius 5/8" and major torus radius of 5-1/4". Figure 25b shows three additional useful parameters: the ring thickness "rt"; the angular arc "aa"; and the slot width "sw". The ring thickness was 1/2", the angular arc was about 25°, and the slot width was 1/4". The 78 turn device operated as a resonant antenna structure at 85 MHz with a radiation resistance of approximately 300 ohms.

Example 9 - Contrawound Helical Torus for Producing Vertical Polarization.

If we could obtain a uniform current distribution over a contrawound toroidal helix of resonant dimensions, we would have the case where $n = 0$. This is especially interesting because E_{ϕ}^m would then vanish, leaving only the field given by

$$(3) E_{\theta}^m = \frac{-\beta a I_m}{2R} J_1(\beta a \sin\theta) e^{j(\omega t - \beta R + \frac{n\pi}{2})}$$

This is an omnidirectional vertically polarized (in the azimuthal plane) resonant radiating toroidal helix. Here we have an equivalent magnetic current flowing along the major circumference of the torus. In this case, it is

necessary to establish a uniform magnetic current along the helical structure in order to make $n = 0$ and cancel out the E_{ϕ}^m component in the radiation field. This mode of operation is especially appealing for VLF antennas.

5 Such a device was constructed as shown in Figure 27 of #10 gauge copper wire. The major radius of the 32 turn toroidal helix was 4-3/4", the minor (or ring) radius was 11/16", the slot width was 3/4", the ring thickness was 1/8" and the resonant frequency was measured as 135 MHz. The
10 antenna of Figure 27 is made by bending the helix of Figure 25b around into a toroid and then dividing it into four parts 2701, 2702, 2703, 2704. The technique employed to obtain the $n = 0$ mode of excitation for the toroidal helix was to
15 simulate a uniform loop by exciting the toroidal helix as the four smaller parts 2701, 2702, 2703, 2704 connected in parallel across a coaxial feedline 2705. This arrangement is the magnetic current analog to the electric current
"cloverleaf" antenna. For a discussion of the electric loop cloverleaf antenna, see Kraus, Antennas, supra, P. 429 and
20 P.H. Smith, "Cloverleaf Antenna for FM Broadcasting", Proceedings of the Institute of Radio Engineers, Vol. 35, PP. 1556-1563, December, 1947. In my toroidal helix, the feed currents cancel, producing no radiation fields and the contrawound resonant toroidal helix supports an effective
25 azimuthally uniform magnetic current which produces the omnidirectional vertically polarized radiation. This structure would also be appropriate as an element in a phase array configuration.

Variable Resonant Frequency

30 Figure 28 shows an embodiment of my invention in which a variable capacitor 2801 is used as a means for varying or tuning the resonant frequency of the antenna without changing the number of turns of the antenna. The antenna of Figure 28 consists of two toroidal helices. One

is fed at points AA' and the other at CC'. The variable capacitor 2801 is placed across the feed points CC'. As the capacitance is varied, the resonant frequency of the antenna is varied.

5 By making use of the slow wave nature of helical structures and the duality between vertical monopoles and magnetic loops, we have been able to construct electrically small, resonant structures with radiation patterns similar to resonant vertical antennas and other antenna arrays. Of
10 course, one does not get something for nothing. The price one pays with the toroidal helix is that it is a narrow band structure (called "high Q") and inherently not a broad band device. These antennas according to the invention which, by virtue of their unique construction, possess a greater
15 radiation resistance than known antennas of similar electrical size without the slow wave winding feature described above. The helix on a torus winding feature permits the formation of a resonant antenna current standing wave in a region of electrically small dimensions, and it permits the controlled
20 variation of antenna currents, resonant frequency, impedance, polarization and antenna pattern.

 Various toroidal helices fall within the scope of the invention. For instance, the helices can have right-hand windings, left-hand windings, bifilar windings in the
25 same direction (both right-hand or both left-hand), or bifilar windings which are contrawound (one right-hand, one left-hand). The toroidal helices can be used with other configurations of the conducting means as well.

 Although the preferred embodiments described above
30 relate to various toroidal helix antenna systems, there are other configurations in which an electrical conducting means cause the antenna system to function as a slow wave device according to the invention, with a velocity factor less than 1 (i.e. $V_f < 1$). The electrical conducting means should be
35 configured to establish a closed standing electromagnetic wave path, the path inhibiting the velocity of propagation

of electromagnetic waves and supporting a standing wave at a predetermined resonant frequency. Such configuration should have a substantially closed loop geometry. Such geometry could be described as being multiply connected. Thus, the electrical conducting means would not have an essentially linear shape, and it would not be a simple circle lying substantially in a single plane (in a strict mathematical sense, a wire or other elongated conductor would necessarily be 3 dimensional and extending in more than one plane, but for the purposes of this discussion an antenna is considered to lie in one plane if it could rest on a flat surface and not rise from that surface more than a small fraction of its length - i.e. a conductor is considered as lying in one plane if in ordinary parlance it could be described as being flat).

A simple ring shaped conductor 3401 of the type shown in Fig. 34 would not satisfy the criteria of the invention. In addition to the toroidal configurations described above, other configurations function to form wave inhibiting devices according to the invention. Thus, in Fig. 29, a conductor 2901 has a wavy pattern and extends around a non-conducting toroidal support 2902. A conductor 3001 is shown in Fig. 30 having a zig-zag shape and is disposed around an imaginary cylinder. Another zig-zag arrangement is shown in Fig. 31, where a conductor 3101 lies in a single plane. The conducting means can lie in a single plane so long as it is noncircular. (It could be circular in projection, if it lies in more than one plane). The conducting means could have linear and curved components, such as the configuration 3201 in Fig. 32. The conducting means need not be a single element or even a plurality of physically connected elements; for example, the antenna 3301 of Fig. 33 comprises a plurality of spaced rings 3302 arranged about a circle. Rings 3302 would be inductively coupled in response to the transmission of electromagnetic waves in antenna 3301. The various antenna arrangements of Figs. 29-33 must be dimensioned and have the characteristics to fulfill the requirement that they

establish a closed standing wave path for electromagnetic waves, which path inhibits the velocity of the waves along the path and supports a standing wave at a preselected resonant frequency.

5 The invention has been described in detail with particular emphasis being placed on the preferred embodiments thereof, but it should be understood that variations and modifications within the spirit and scope of the invention
10 may occur to those skilled in the art to which the invention pertains.

The invention may be summarized as follows:

1. An electromagnetic wave antenna system comprising:
electrical conducting means for establishing a closed standing electromagnetic wave path in response to the transmission of electromagnetic energy in said antenna,
5 said path inhibiting the velocity of propagation of electromagnetic waves in said antenna and said path supporting a standing electromagnetic wave at a predetermined resonant frequency.
- 10 2. The invention according to item 1 wherein said conducting means has a substantially closed loop configuration and a velocity factor (V_f) less than one.
- 15 3. The invention according to items 1 or 2 wherein said electrical conducting means comprises an electrical conductor having a substantially closed loop configuration and a non-circular shape in a single plane.
- 20 4. The invention according to item 1 wherein said electrical conducting means comprises an electrical conductor wound more than once about an axis and having a substantially closed geometric shape.
5. The invention according to item 1 wherein said electrical conducting means has the configuration of a multiply connected geometry.
- 25 6. The invention according to items 1, 4 or 5 wherein said electrical conducting means comprises a helically wound elongated electrical conductor.

7. The invention according to item 1 wherein said electrical conducting means comprises an electrical conductor wound about a non-conducting support means.

5 8. The invention according to item 7 wherein said support means has a substantially closed geometric shape.

9. The invention according to item 8 wherein said support means is in the shape of a torus.

10 10. The invention according to items 8 or 9 wherein said electrical conductor is helically wound about said support means.

15 11. The invention according to items 1 or 7 wherein said electrical conducting means comprises a continuous conductive winding, said winding being configured in a substantially closed geometric shape.

12. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises an electrical conductor having multiple progressive windings.

20 13. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises a multiply-wound helical elongated conductor.

14. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises more than one toroidal loop.

25 15. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises means for producing a vertically polarized radiation pattern.

16. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises means for producing a horizontally polarized radiation pattern.

5 17. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises means for producing an omnidirectional vertically polarized radiation pattern.

10 18. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises first toroidal loop means having a first direction of loop current and producing a first azimuthal plane radiation pattern, and second toroidal loop means having a second direction of loop current opposite the first direction and producing a second toroidal loops together producing a polarization pattern in
15 a single plane, in response to the transmission of electromagnetic energy in said antenna system.

19. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises a quadrifilarly wound toroidal helix, said helix including
20 two superimposed bifilar helices adapted to be fed in phase quadrature.

20. The invention according to items 1, 7, 8 or 9 hwerein said electrical conducting means comprises means for producing a circularly polarized radiation pattern in
25 response to the transmission of electromagnetic energy in said antenna system.

21. The invention according to items 1, 7, 8 or 9 wherein said electrical conducting means comprises a first toroidal loop means having a first current distribution and a second toroidal loop having a second current distribution rotated 90° from the first current distribution, said first and second toroidal loops together producing a circular polarization in the azimuthal plane when the loops are excited in phase quadrature.

22. The invention according to item 1 wherein said electrical conducting means comprises an array.

23. The invention according to item 22 wherein said electrical conducting means comprises a driven portion and a parasitic portion, at least one of said portions having a toroidal loop configuration.

24. The invention according to item 22 wherein said driven portion comprises a resonant linear element.

25. The invention according to item 22 or 23 wherein said parasitic portion comprises a tuned toroidal loop.

26. The invention according to items 7, 8 or 9 wherein said electrical conducting means is a bifilar toroidal loop.

27. The invention according to items 7, 8 or 9 wherein said electrical conducting means is a rectangular toroidal loop.

28. The invention of item 1, wherein said electrical conducting means comprises contrawound toroidal helices.

29. An antenna having a primary resonant frequency corresponding to a selected wavelength (" λ_0 "), comprising:

5 a first conductor formed in a first helix, the centerline axis of said first helix being formed in a first loop, wherein the radius (" a ") of said first loop, the radius (" b ") of each turn of said first helix, and the number (" N ") of turns of said first helix, are approximated by the formula

$$\frac{2\lambda a}{\lambda_0} = \frac{1}{[1 + 20(\frac{2b}{s})^{5/2} (2b/\lambda_0)^{1/2}]^{1/2}}$$

10 and wherein a and b are each less than λ_0 .

30. The invention of item 28, wherein said first conductor is continuous.

31. The invention of item 28, wherein said first conductor has two ends located near each other, said two
15 ends of said first conductor being feed points for said first conductor.

32. The invention of item 30, further comprising:
a second conductor formed into a second helix,
the centerline axis of said second helix being formed into
20 a second loop coincident with said first loop, wherein the radius of each turn of said second helix is the same as the radius of each turn of said first helix, wherein said first and second helixes have the same number of turns, and
wherein the turns of said first helix are spaced from the
25 turns of said second helix; and

said second conductor having two ends located near each other and opposite said two ends of said first conductor, said two ends of said second conductor being feed points for second conductor.

33. The invention of item 31, wherein current flows in the same direction around said loops through said first and second conductors, whereby a horizontally-polarized antenna is formed when the plane of said loops is horizontal.

34. The invention of item 32, wherein current flows in opposite directions around said loops through said first and second conductors, whereby a vertically-polarized antenna is formed when the plane of said loops is horizontal.

35. The invention of item 31, further comprising:
a third conductor formed into a third helix, the centerline axis of said third helix being formed into a third loop coincident with said first loop, the radius of each turn of said third helix being the same as the radius of each turn of said first helix, said third and first helices having the same number of turns, and the turns of said third helix being spaced from the turns of said first and second helices;

said third conductor having two ends located near each other and midway between said ends of said first helix and said ends of said second helix, said ends of said third conductor being feed points for said third conductor;

a fourth conductor formed into a fourth helix, the centerline axis of said fourth helix being formed into a fourth loop coincident with said first loop, the radius of each turn of said fourth helix being the same as the radius of each turn of said first helix, said fourth and first helices having the same number of turns, and the turns of said fourth helix being spaced from said first, second, and third helices; and

said fourth conductor having two ends located near each other and opposite said two ends of said third helix, said two ends of said fourth conductor being feed points for said fourth conductor.

36. The invention of item 34, wherein current flows in opposite directions around said loop through said first and second conductors, wherein current flows in opposite directions around said loop through said third and fourth conductors, and wherein said first and second conductors are fed in phase quadrature in relation to said third and fourth conductors, whereby an omnidirectional vertically polarized antenna is formed when the plane of said loops is horizontal.

37. The invention of item 34, wherein current flows in the same direction around said loop through said first and second conductors, wherein current flows in the same direction around said loop through said third and fourth conductors, and wherein said first and second conductors are fed in phase quadrature in relation to said third and fourth conductors, whereby an omnidirectional horizontally polarized antenna is formed when the plane of said loops is horizontal.

38. The invention of item 28, further comprising:
a second antenna spaced from said first conductor and directly driven to be phase shifted from said first conductor, whereby a driven antenna array is formed.

39. The invention of item 28, further comprising:
a second antenna spaced from said first conductor and excited by the field produced by said first conductor, whereby a parasitic antenna array is formed.

40. The invention of item 28, further comprising:
a second antenna spaced from said first conductor, wherein said first conductor is excited by the field produced by said second antenna, whereby a parasitic antenna array is formed.

CLAIMS:

1. An electromagnetic wave antenna system comprising:
electrical conducting means for establishing a closed standing electromagnetic wave path in response to the transmission of electromagnetic energy in said antenna,

CHARACTERIZED IN THAT said path inhibits the velocity of propagation of electromagnetic waves in said antenna and supports a standing electromagnetic wave at a predetermined resonant frequency.

2. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said conducting means has a substantially closed loop configuration and a velocity factor (V_f) less than one.

3. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said electrical conducting means comprises an electrical conductor having a substantially closed loop configuration and a non-circular shape in a single plane.

4. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said electrical conducting means comprises an electrical conductor wound more than once about an axis and having a substantially closed geometric shape.

5. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said electrical conducting means has the configuration of a multiply connected geometry.

6. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said electrical conducting means comprises an electrical conductor wound about a non-conducting support means.

7. The invention according to claim 1, FURTHER CHARACTERIZED IN THAT said electrical conducting means comprises a driven array including a driven portion and a parasitic portion, at least one of said portions having a toroidal loop configuration.

8. An antenna having a primary resonant frequency corresponding to a selected wavelength (" λ_0 ")

CHARACTERIZED IN THAT said antenna comprises:

a first conductor formed in a first helix, the center-line of said first helix being formed in a first loop, wherein the radius (" a ") of said first loop, the radius (" b ") of each turn of said first helix, and the number (" N ") of turns of said first helix, are approximated by the formula

$$\frac{2\pi a}{\lambda_0} = \frac{1}{[1 + 20 \left(\frac{2b}{s}\right)^{5/2} (2b/\lambda_0)^{1/2}]^{1/2}}$$

and wherein a and b are each less than λ_0 .

9. The invention of claim 8, CHARACTERIZED IN THAT said antenna further comprises:

a second conductor formed into a second helix, the centerline axis of said second helix being formed into a second loop coincident with said first loop, wherein the radius of each turn of said second helix is the same as the radius of each turn of said first helix, wherein said first and second helixes have the same number of turns, and wherein the turns of said first helix are spaced from the turns of said second helix; and

said second conductor having two ends located near each other and opposite said two ends of said first conductor, said two ends of said second conductor being feed points for second conductor.

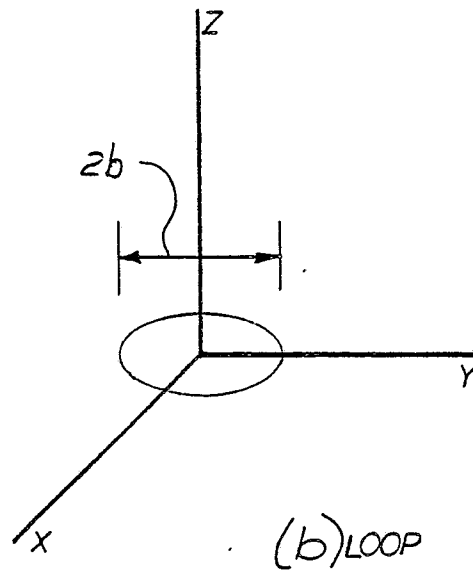
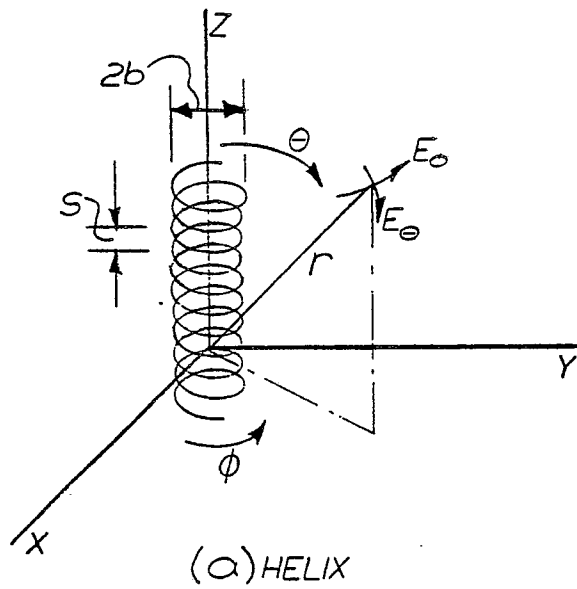
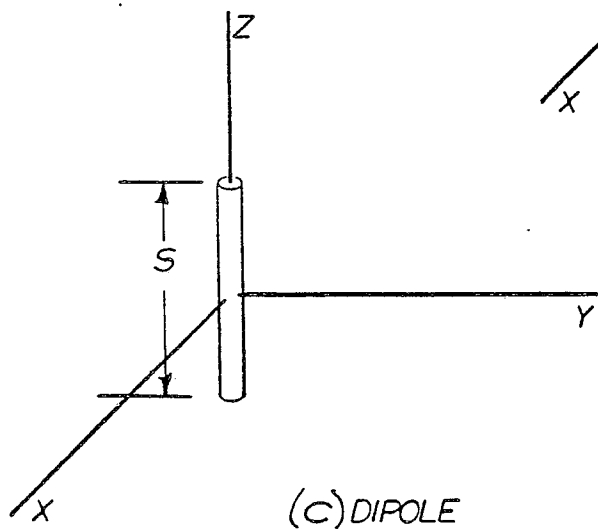


FIG. 1 PRIOR ART



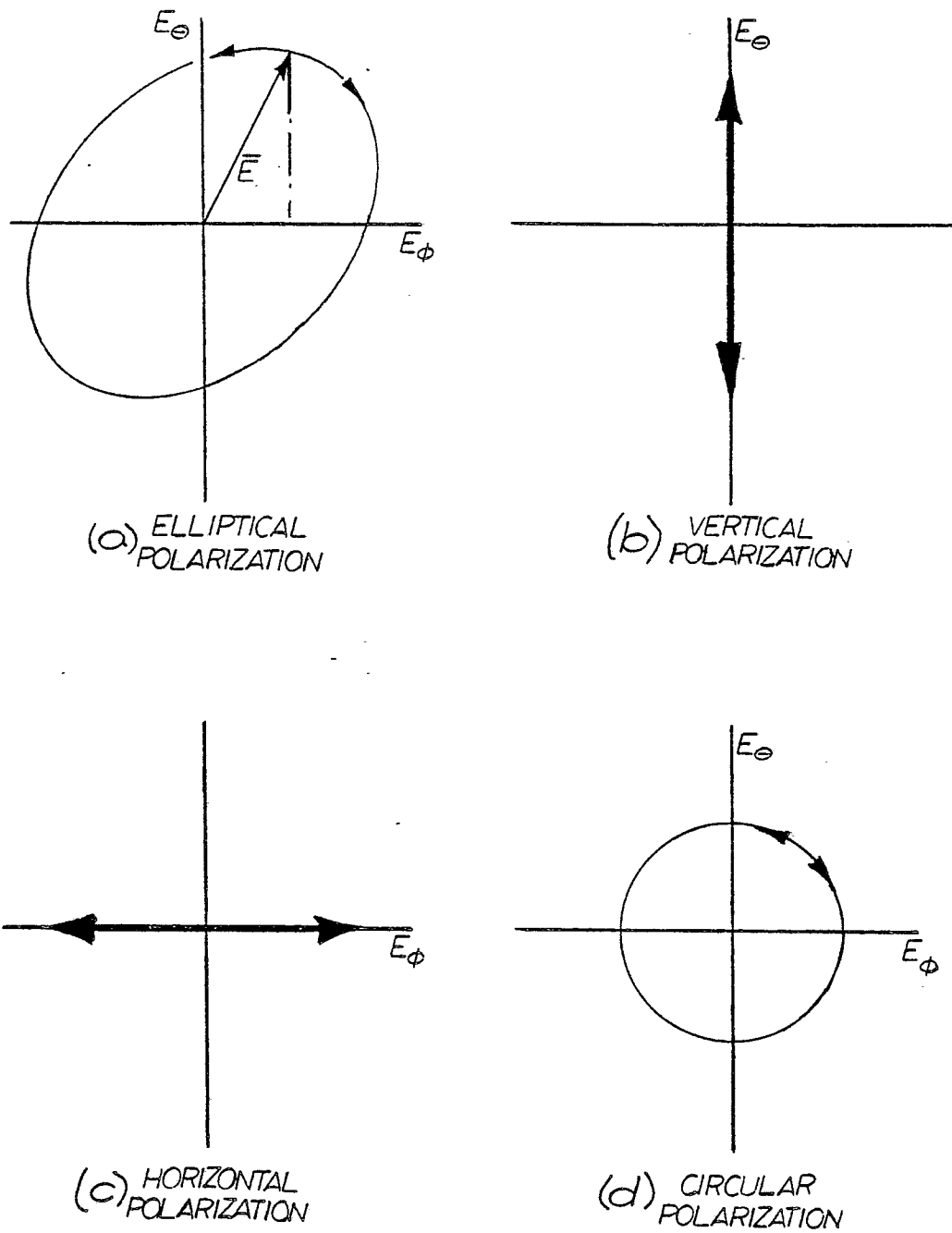
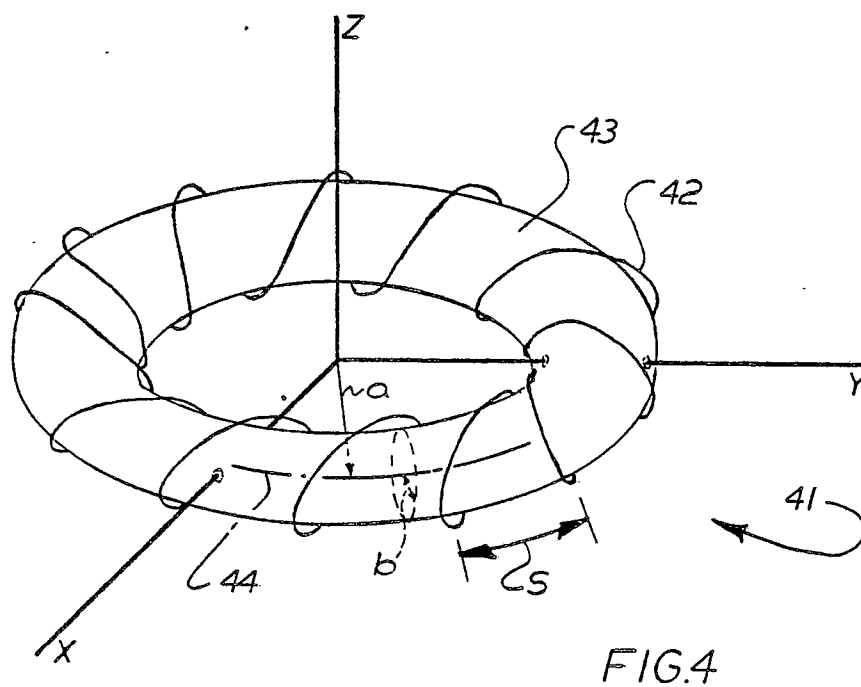
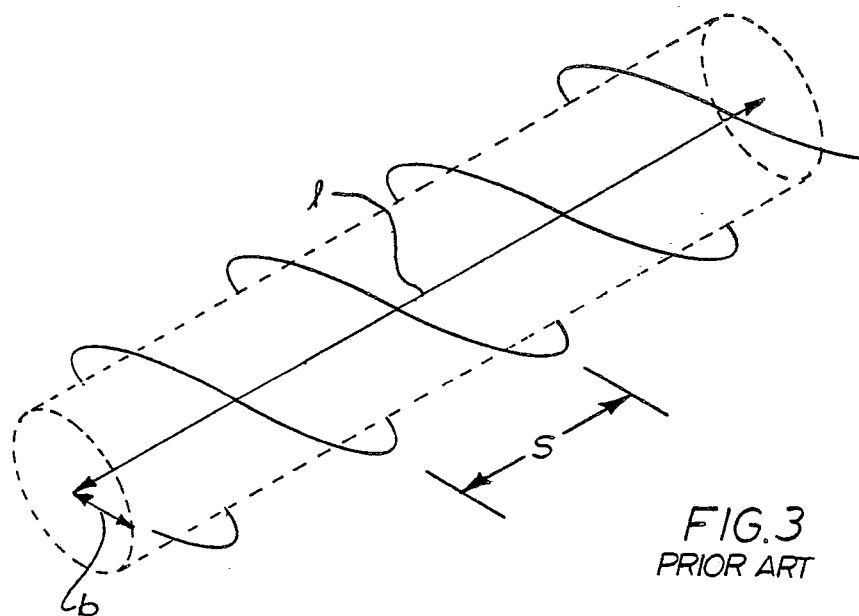


FIG. 2



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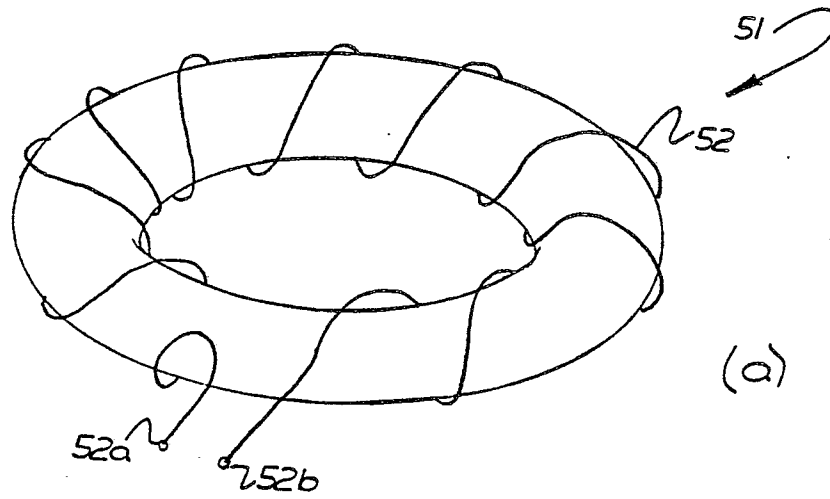
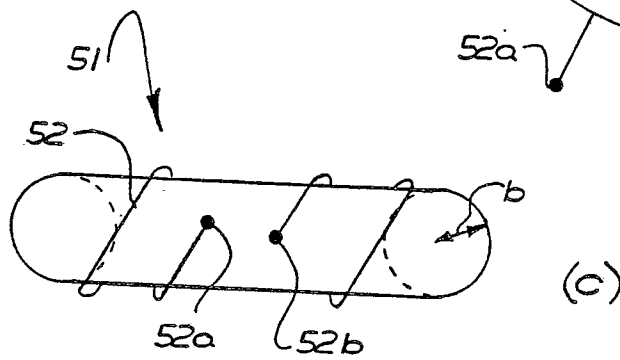
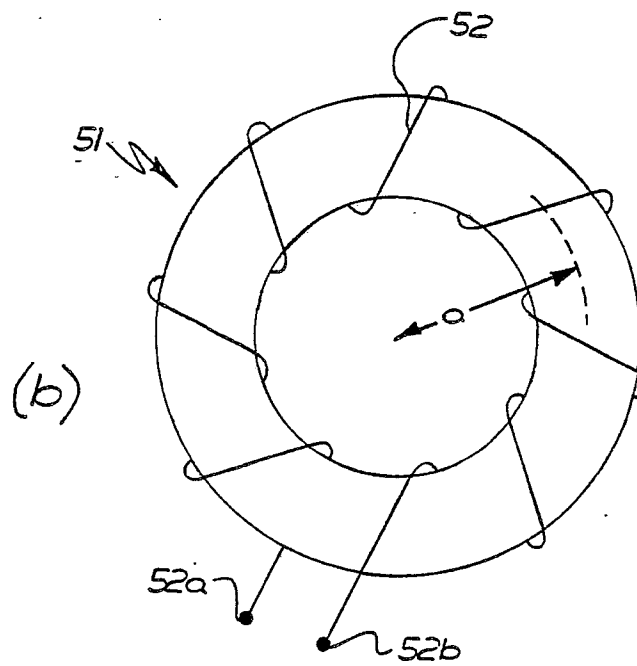


FIG. 5



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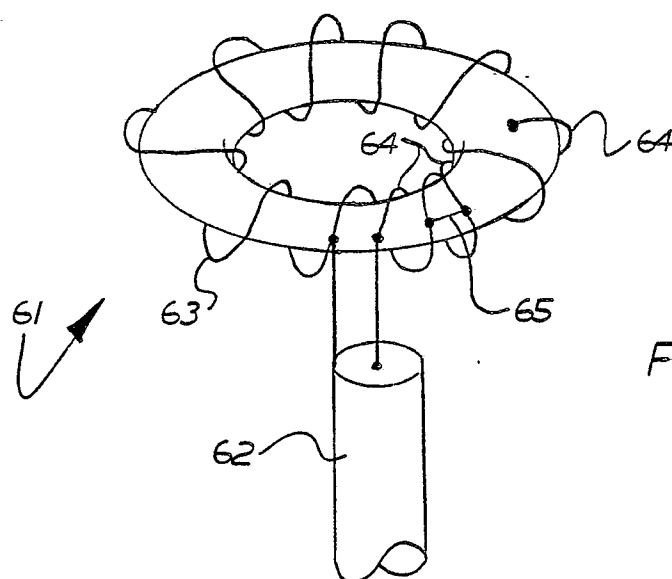


FIG. 6

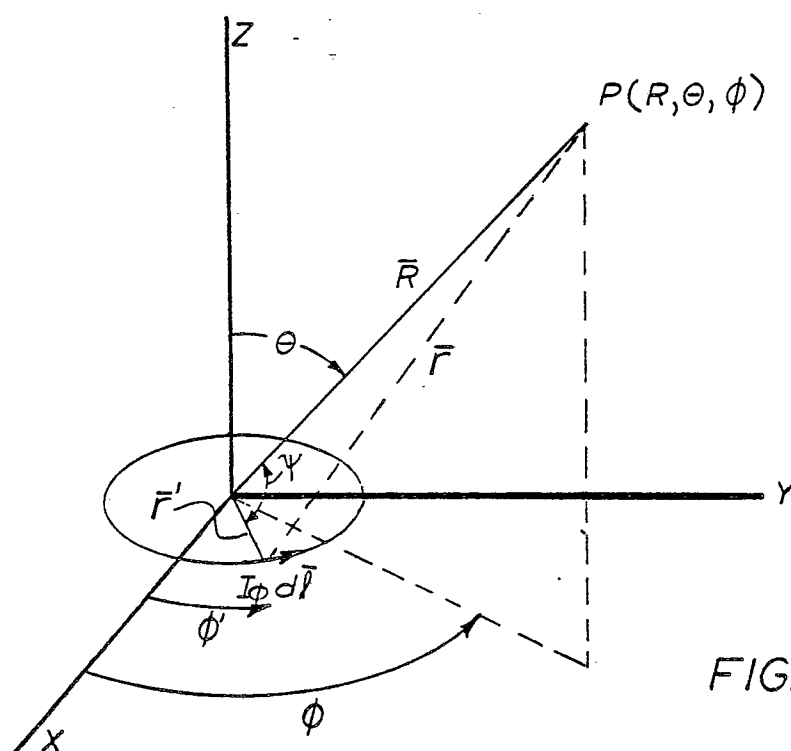
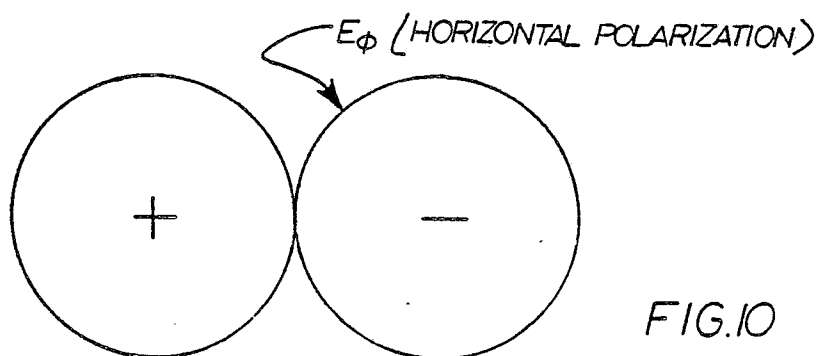
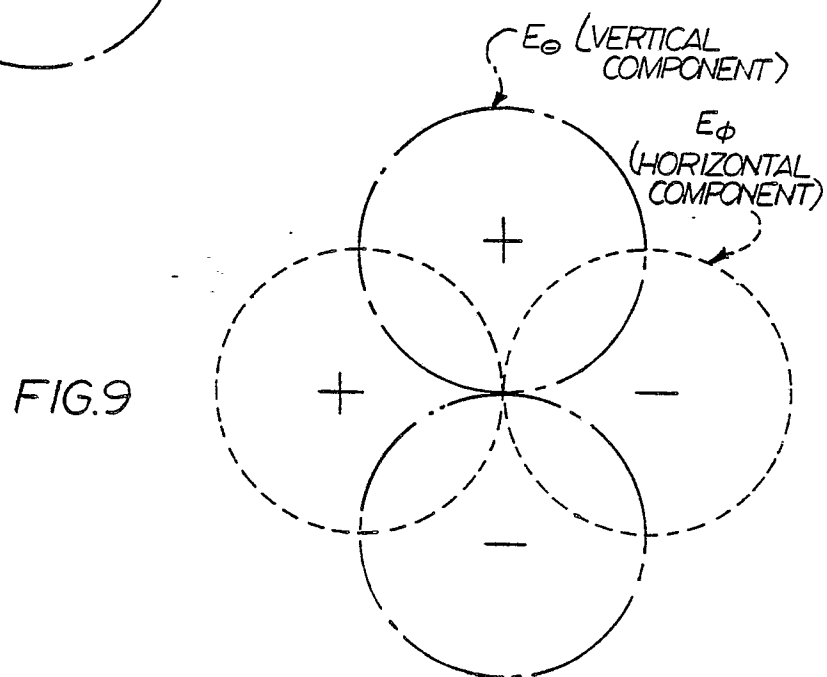
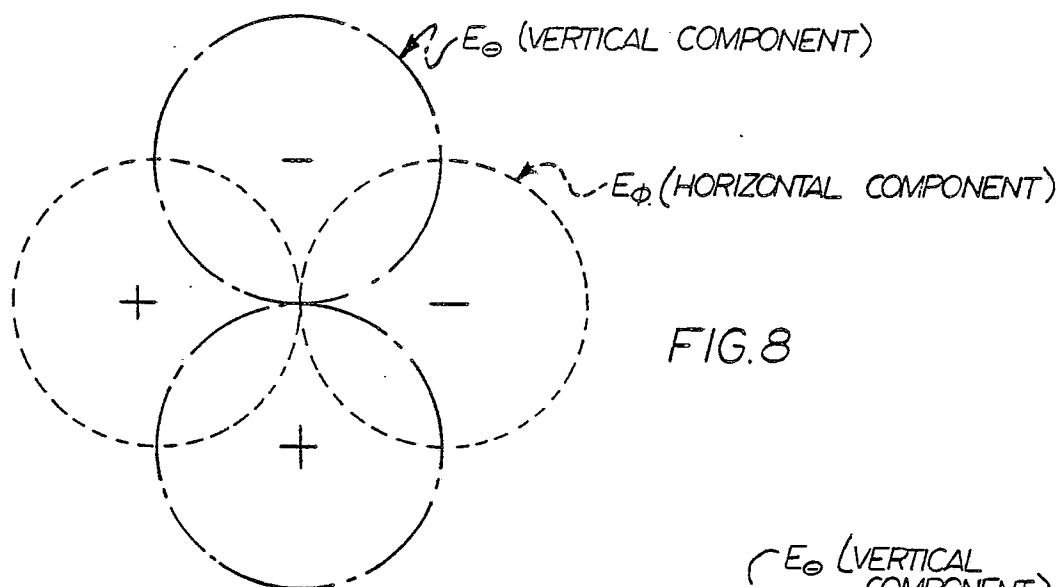
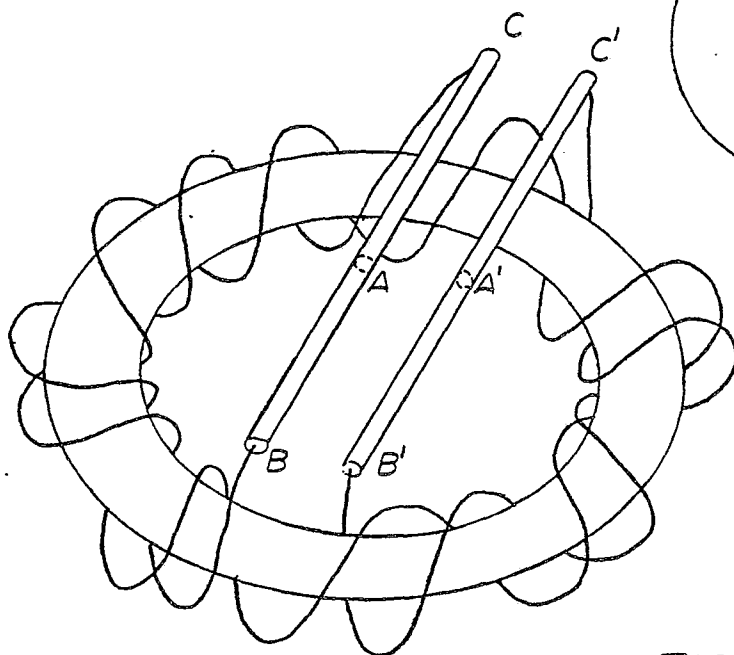
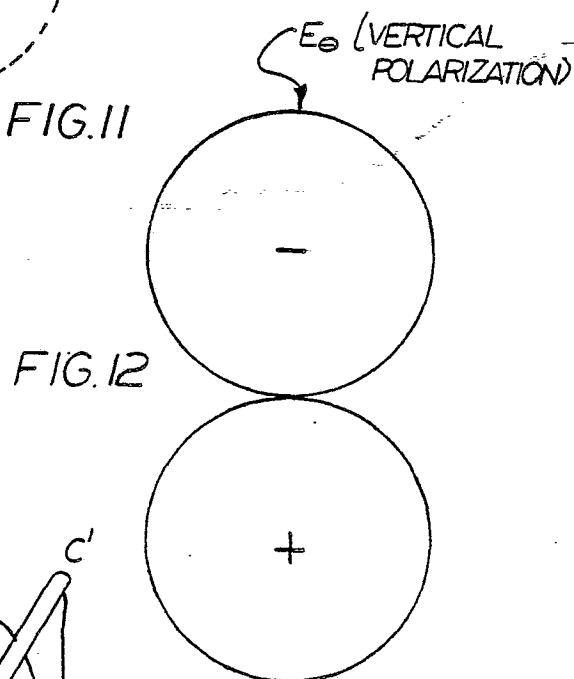
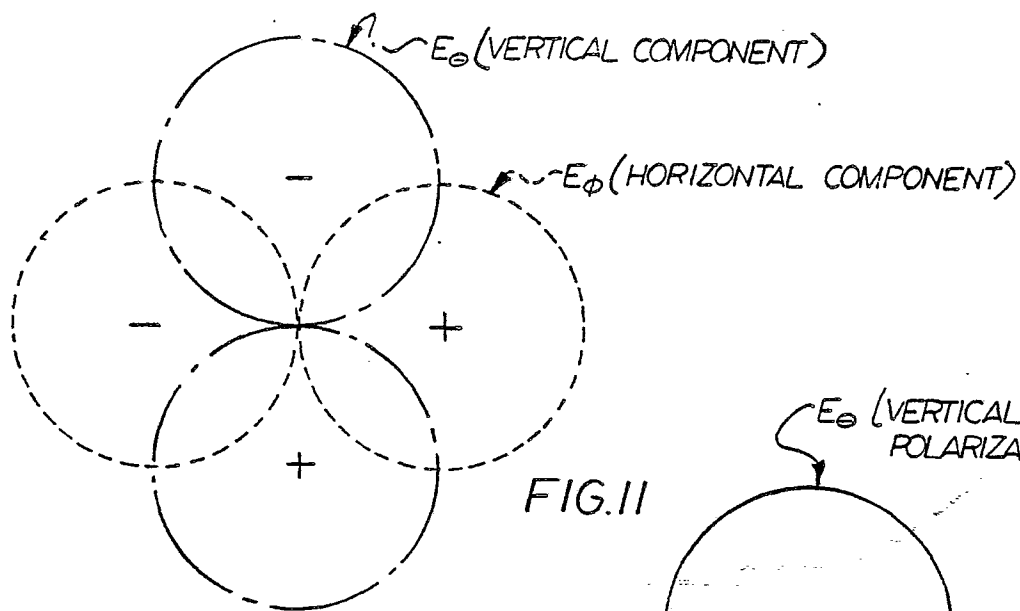
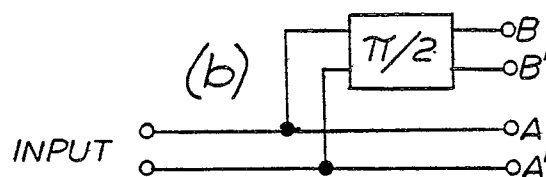
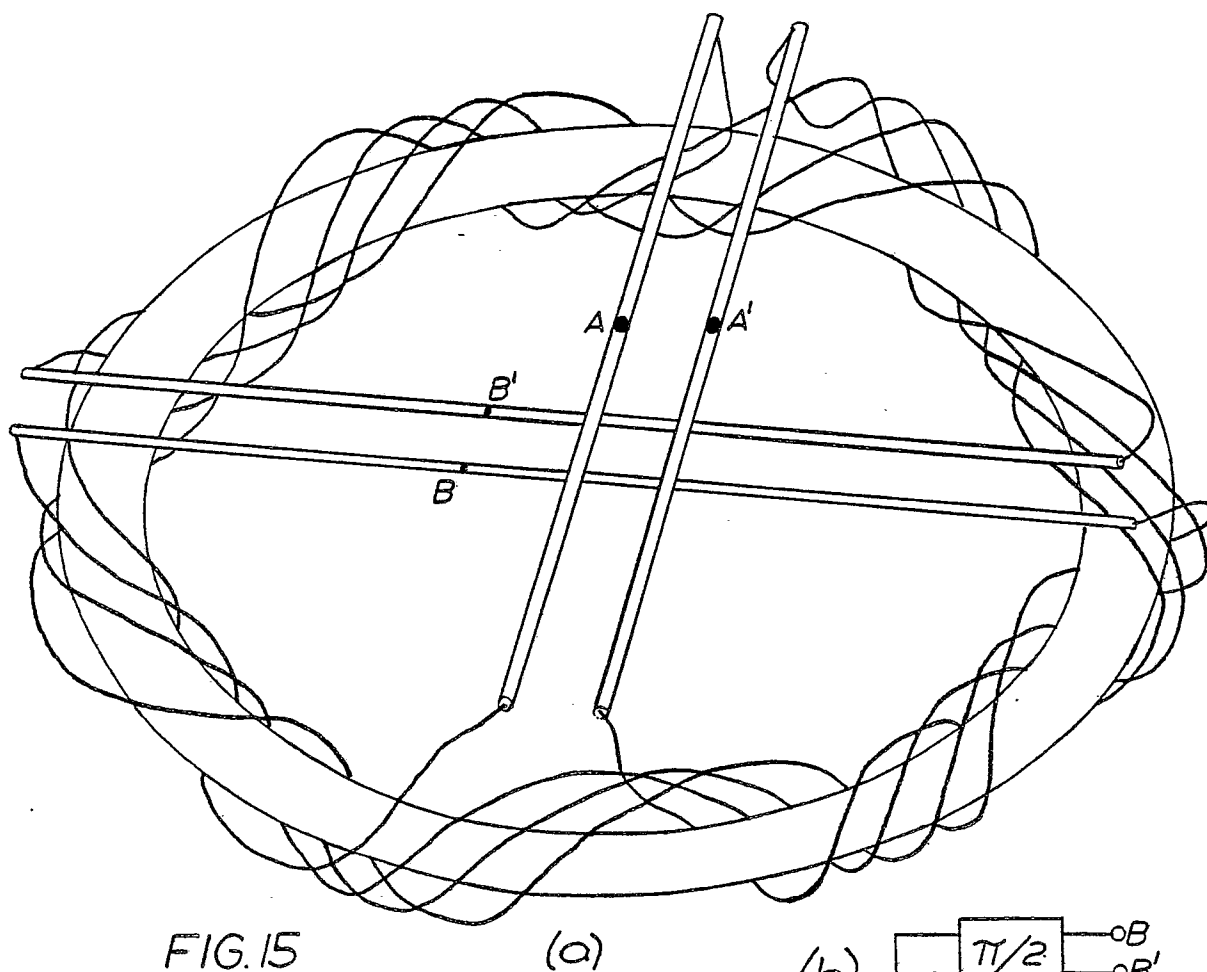
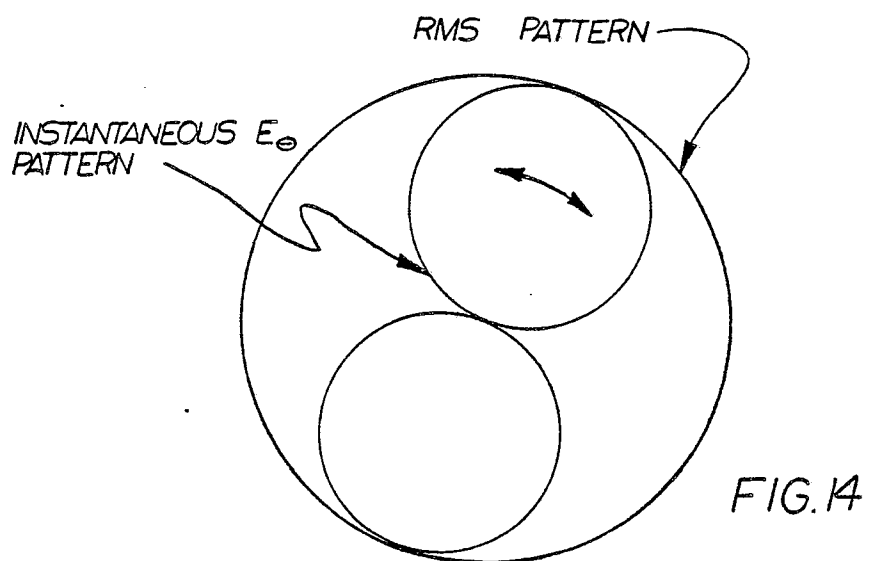


FIG. 7

$$\begin{aligned}\vec{r}' &= a\hat{r} \\ \vec{r} &= \vec{R} - \vec{r}'\end{aligned}$$







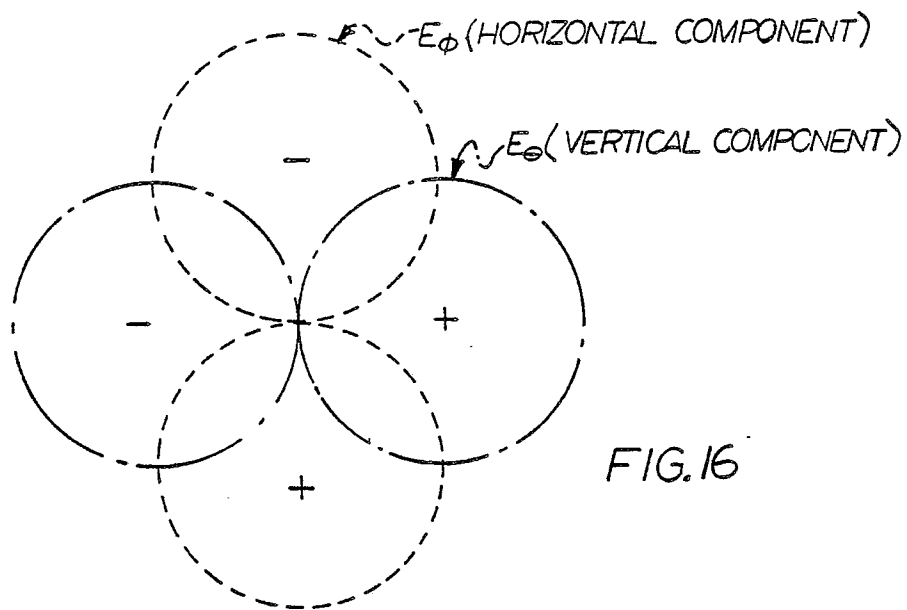


FIG. 16

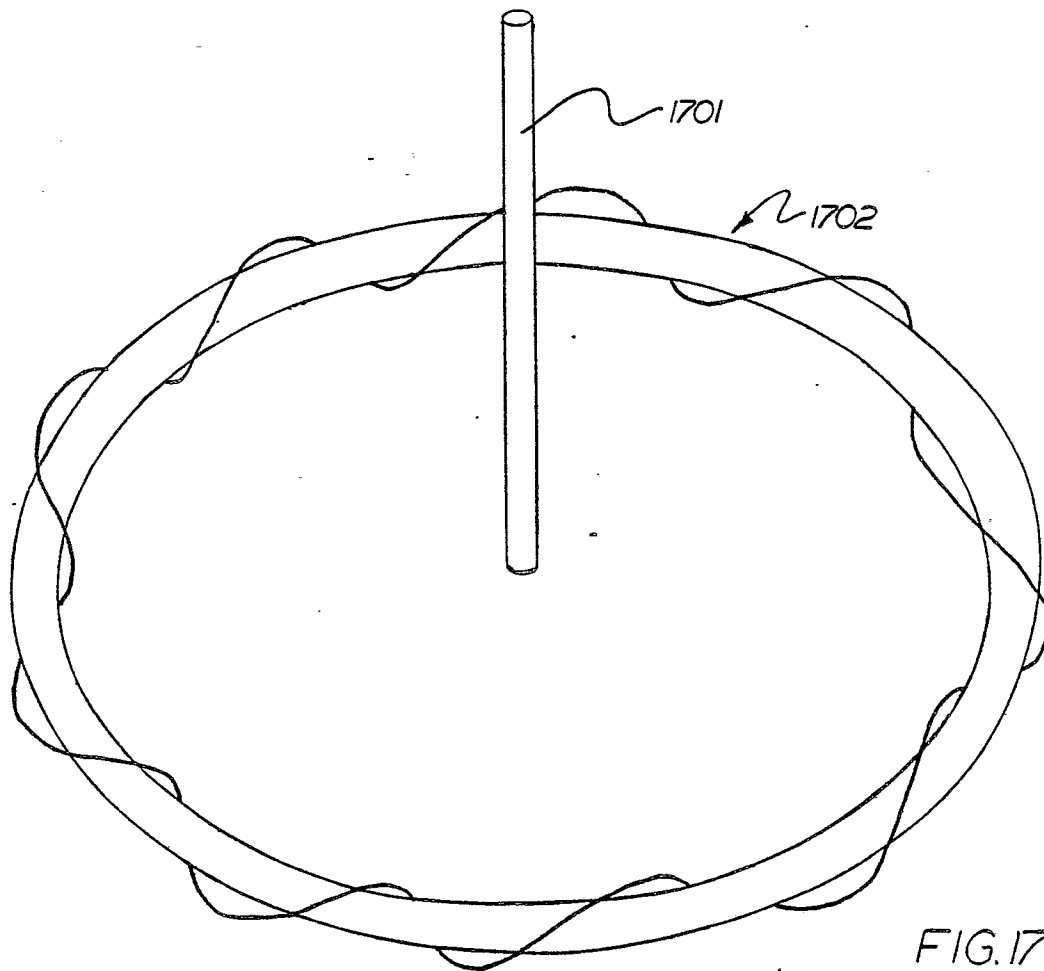
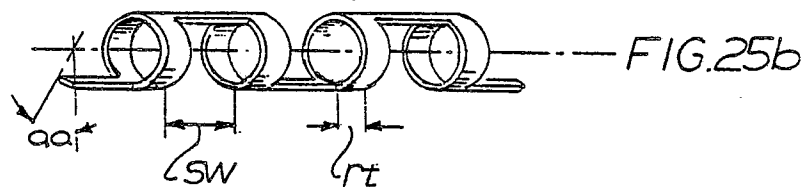
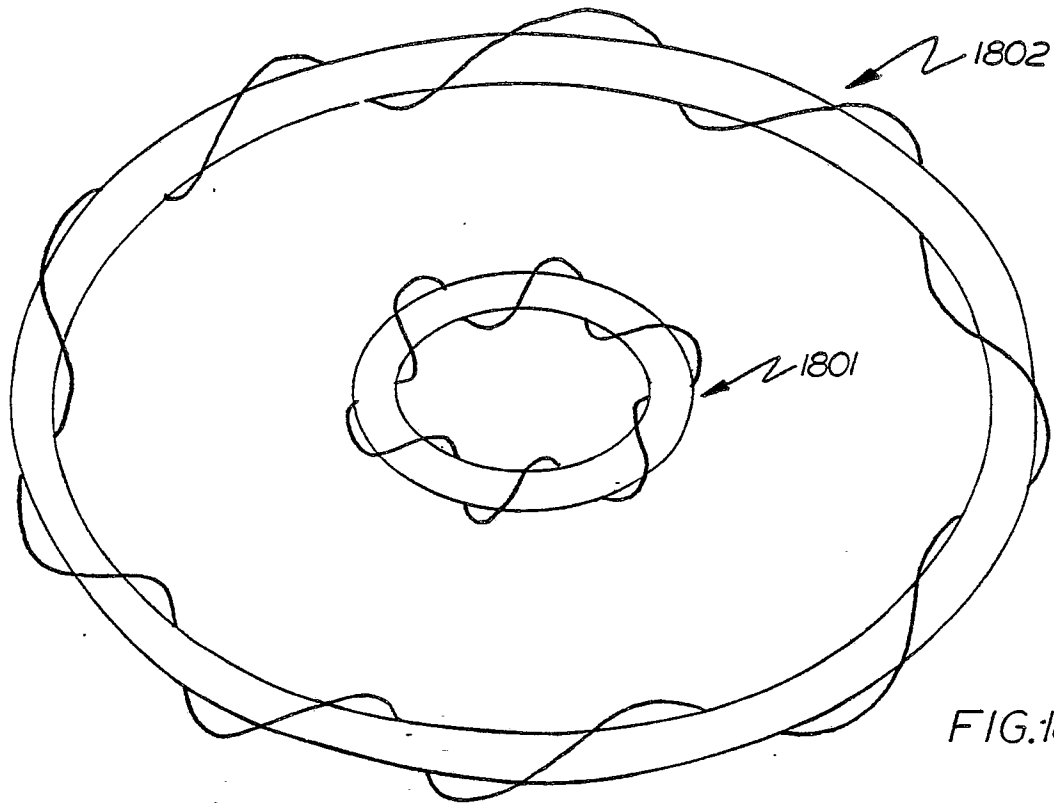


FIG. 17

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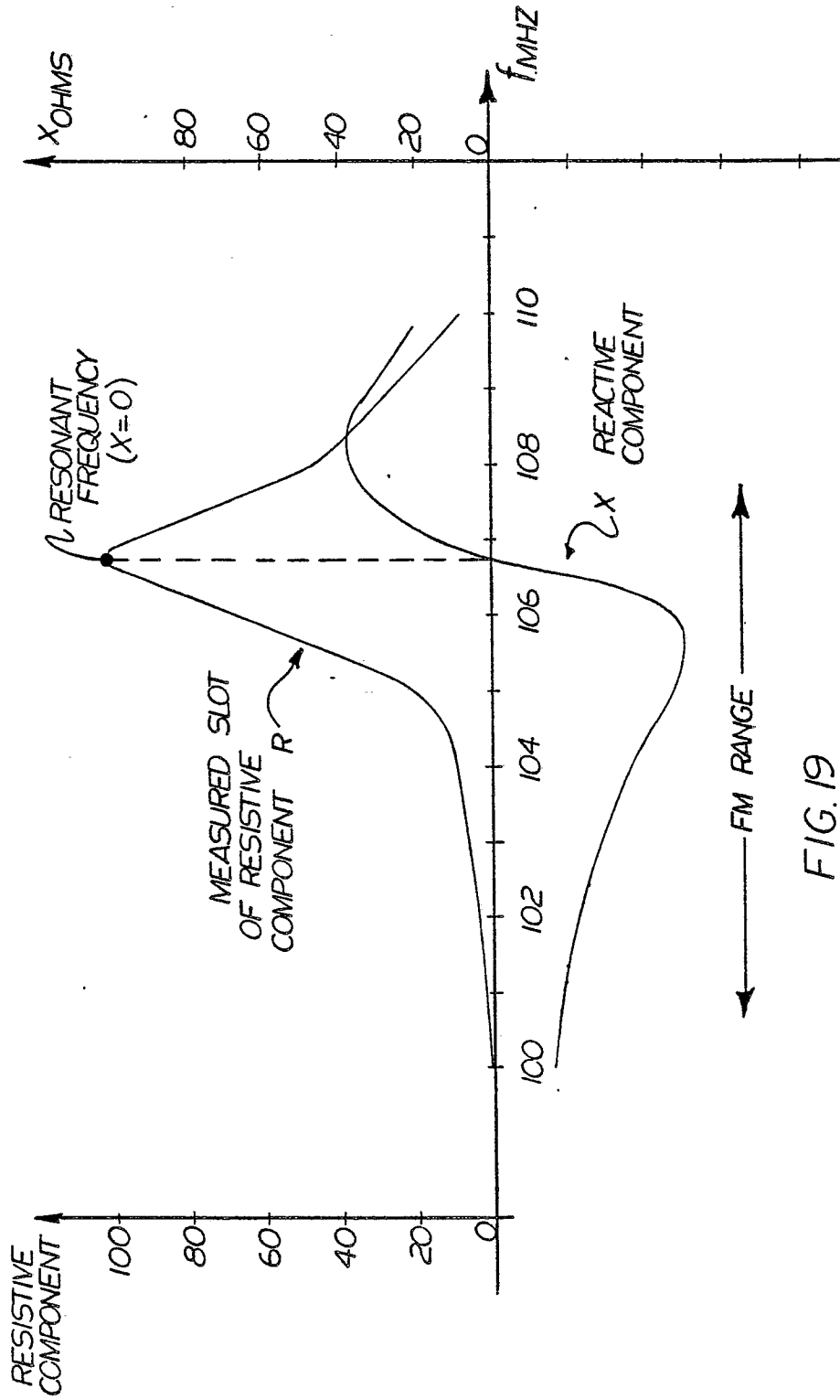


FIG. 19

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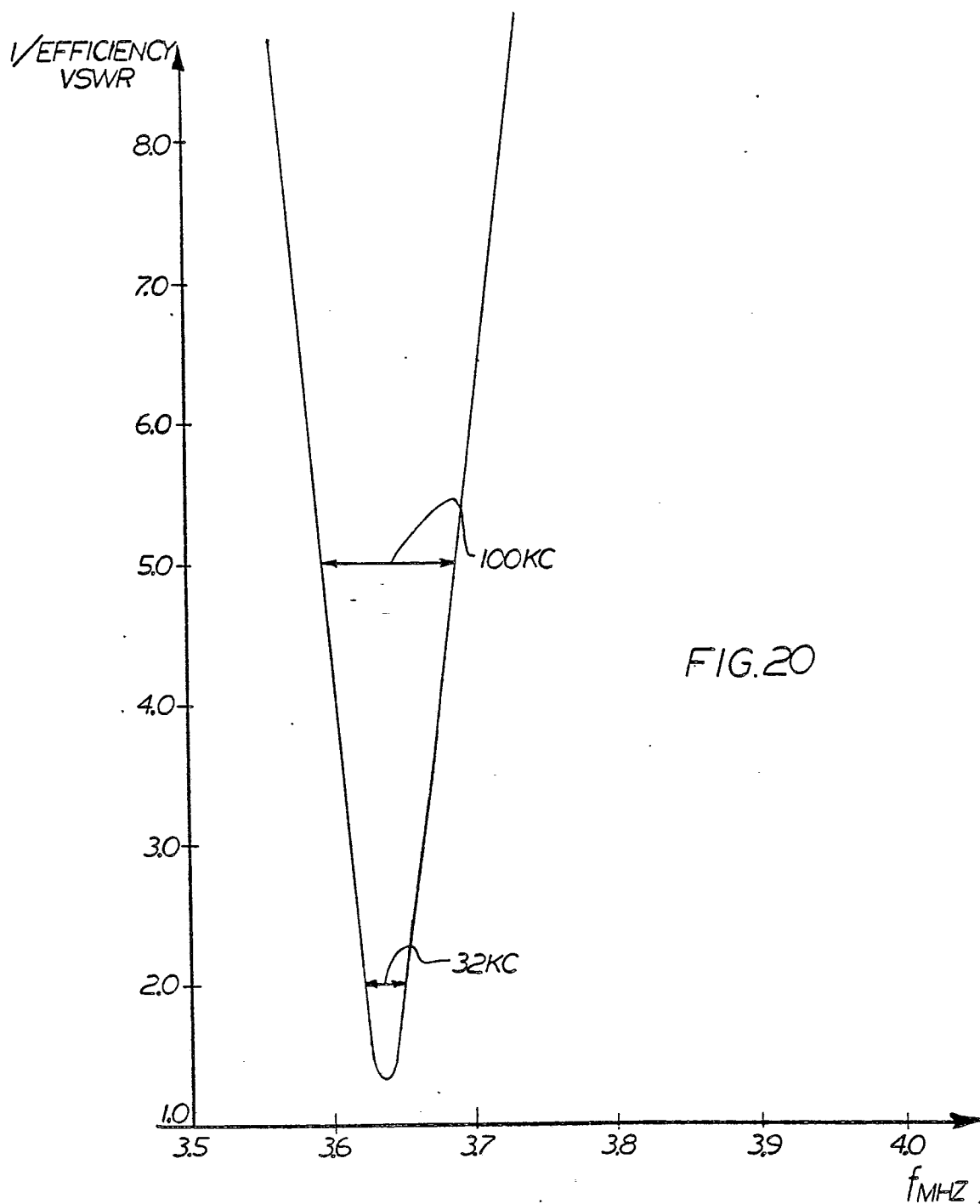
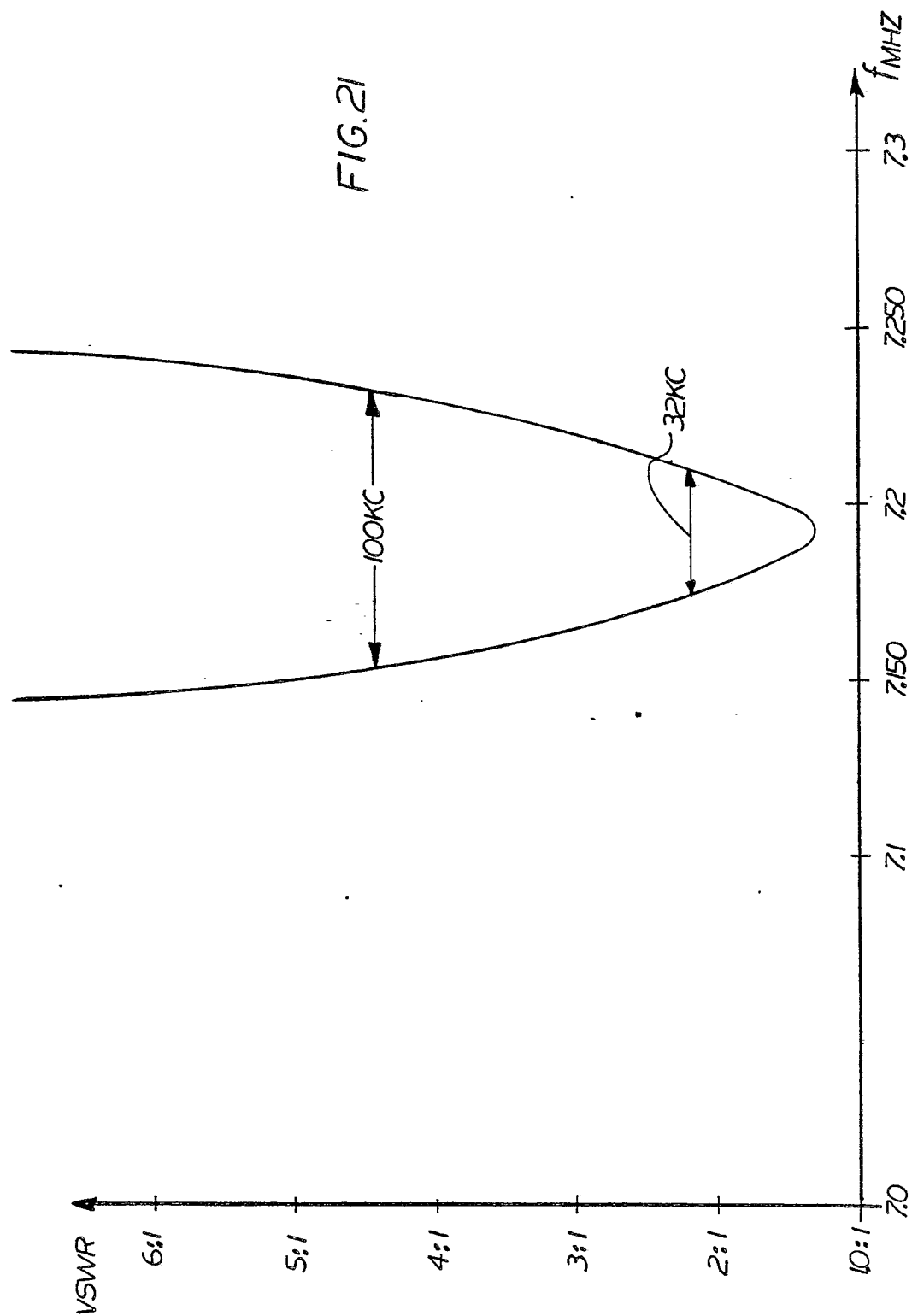


FIG.20

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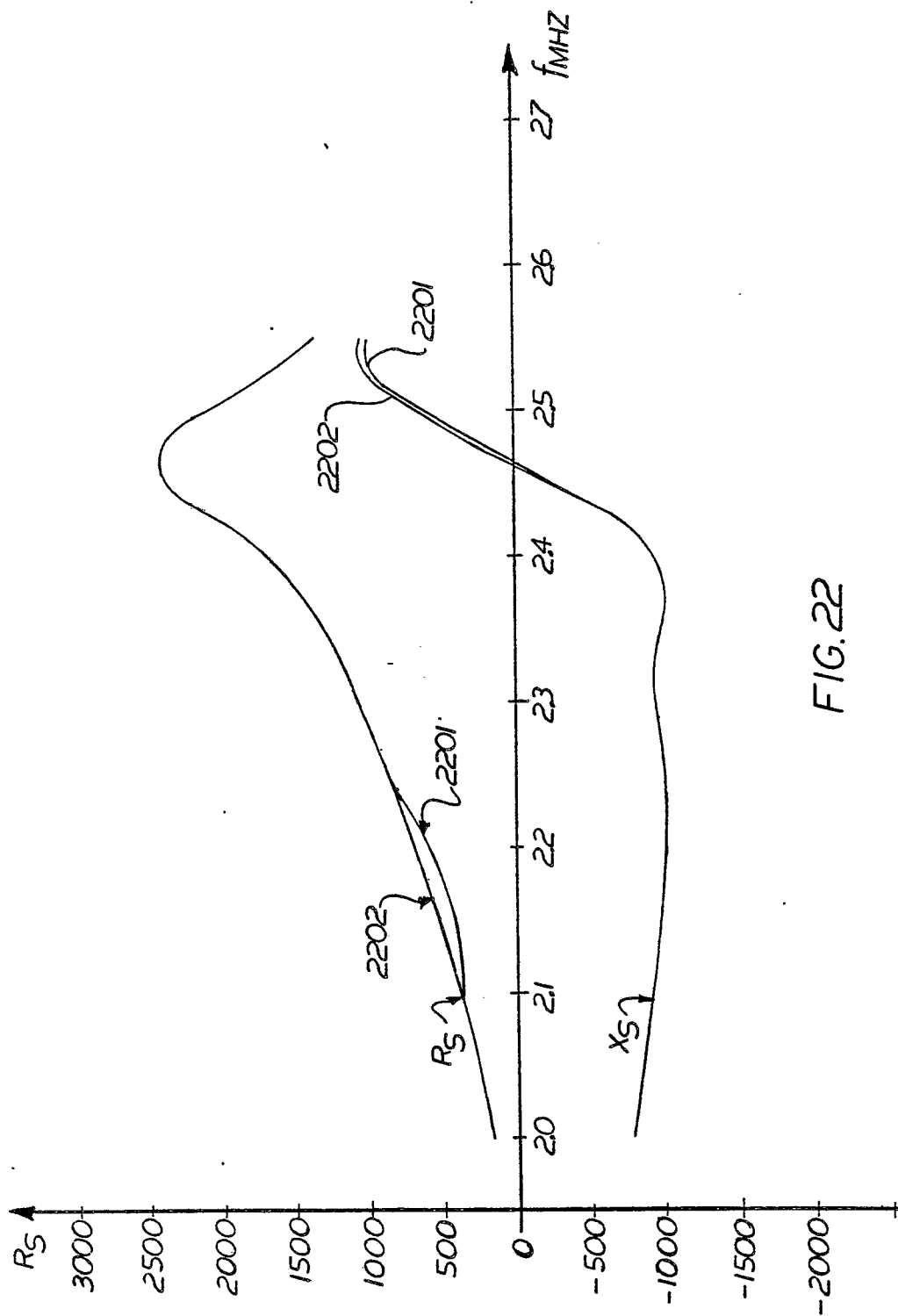


FIG. 22

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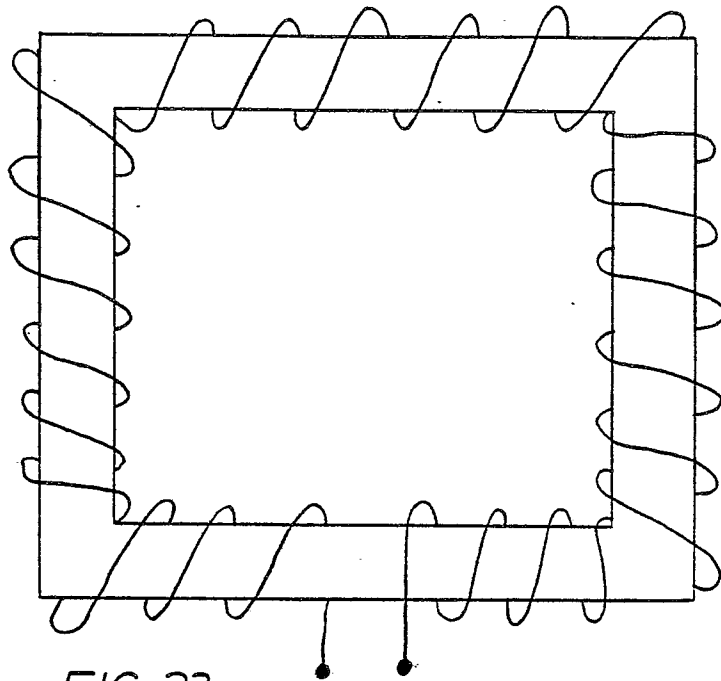


FIG. 23

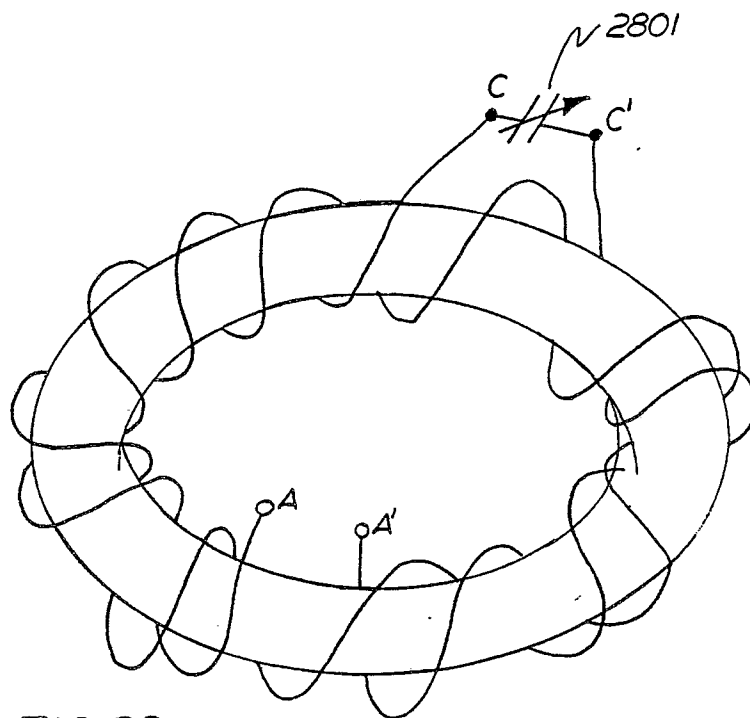


FIG. 28

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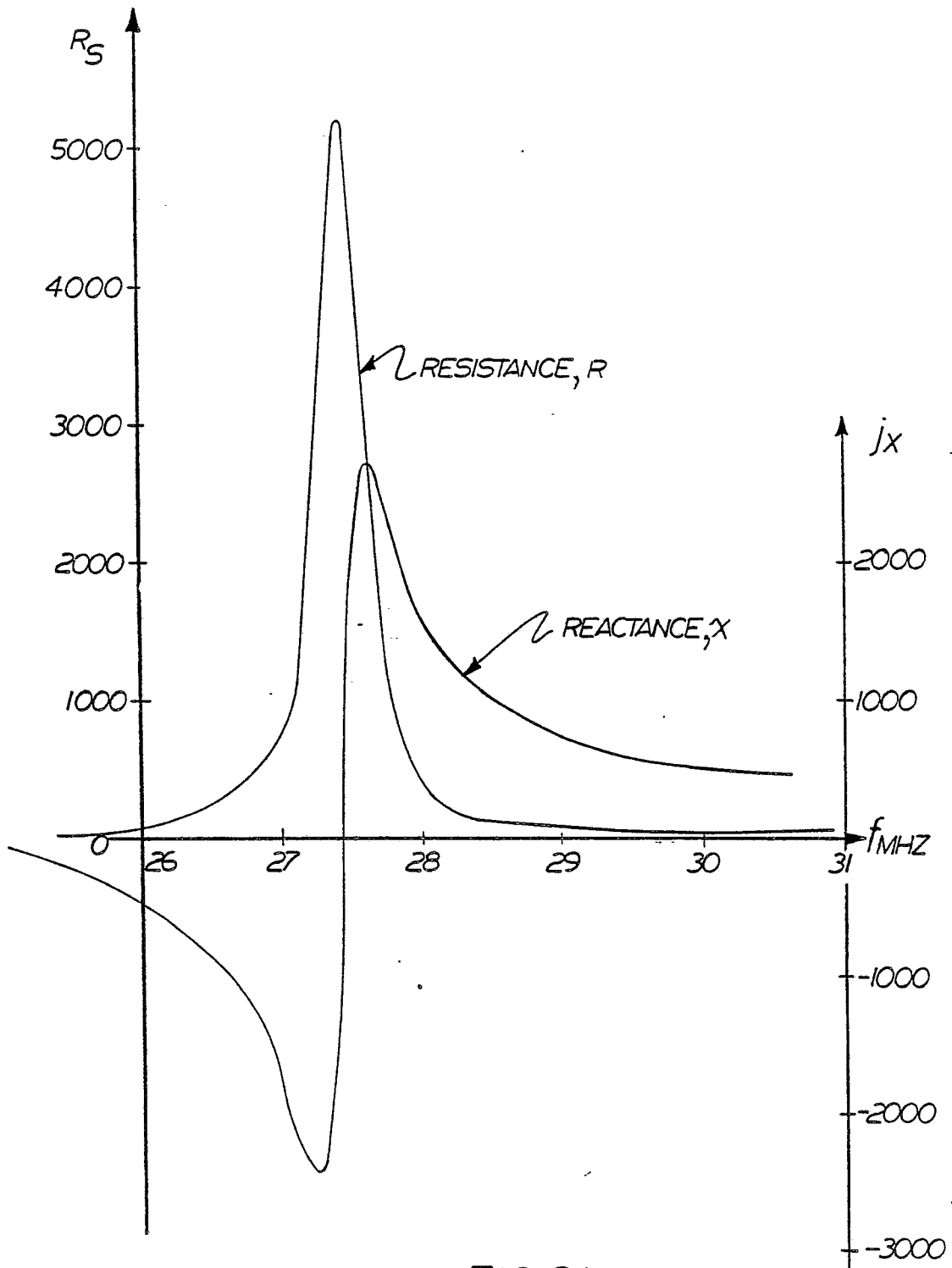


FIG.24

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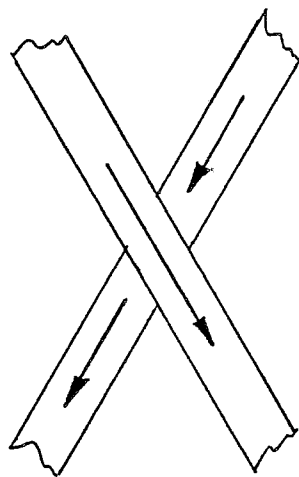
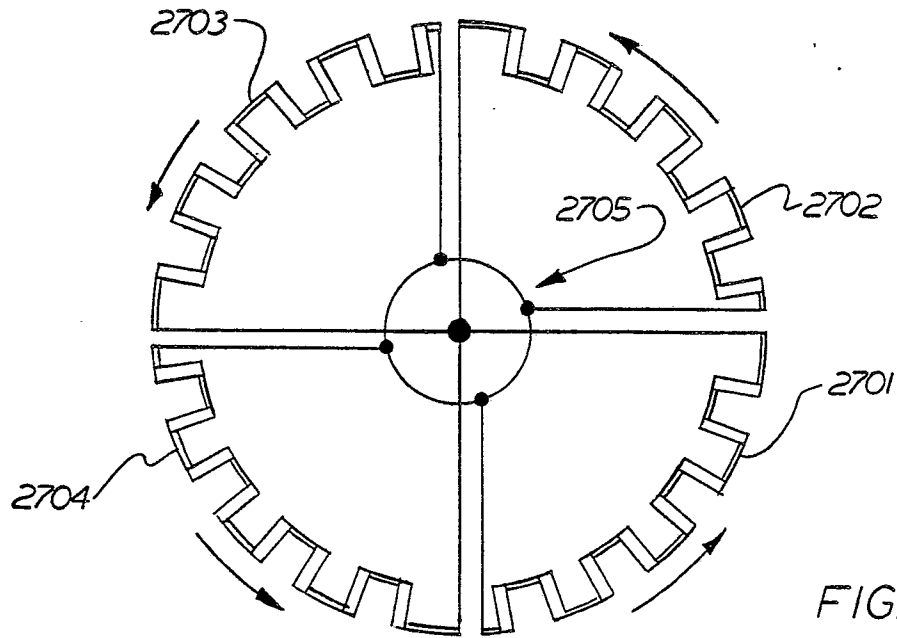


FIG. 26a

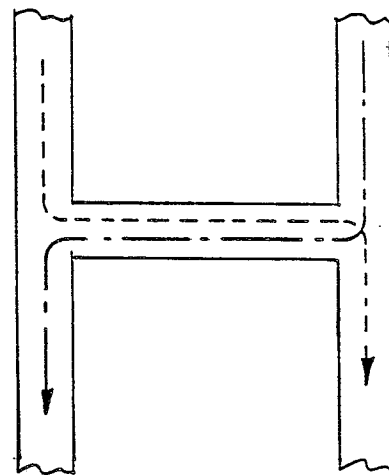
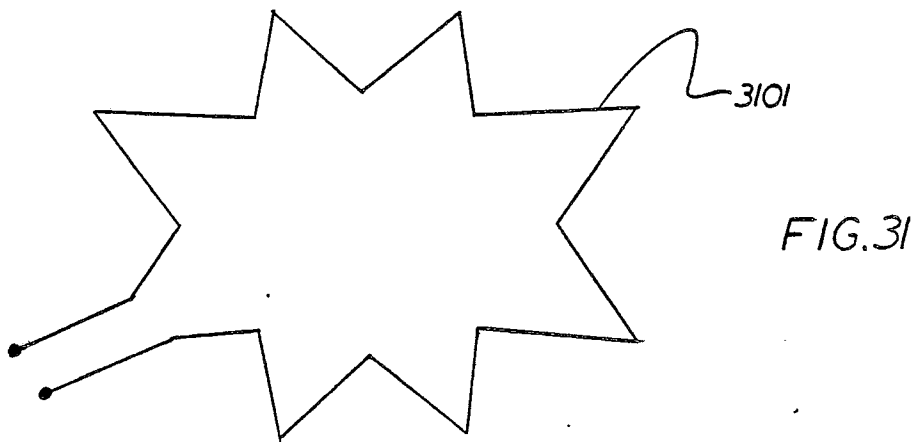
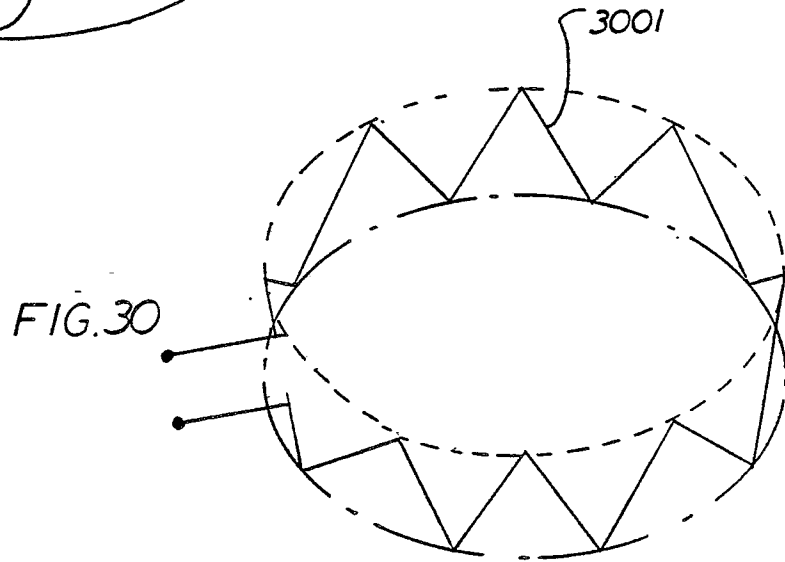
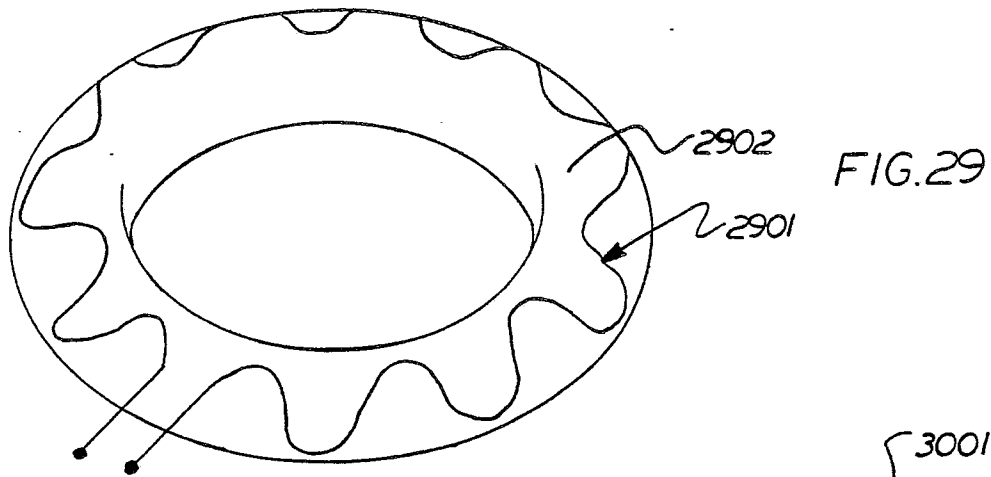


FIG. 26b

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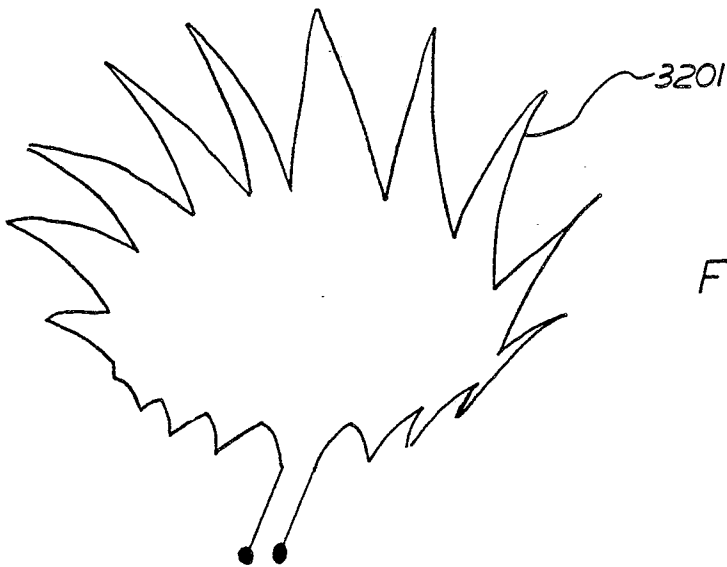


FIG. 32

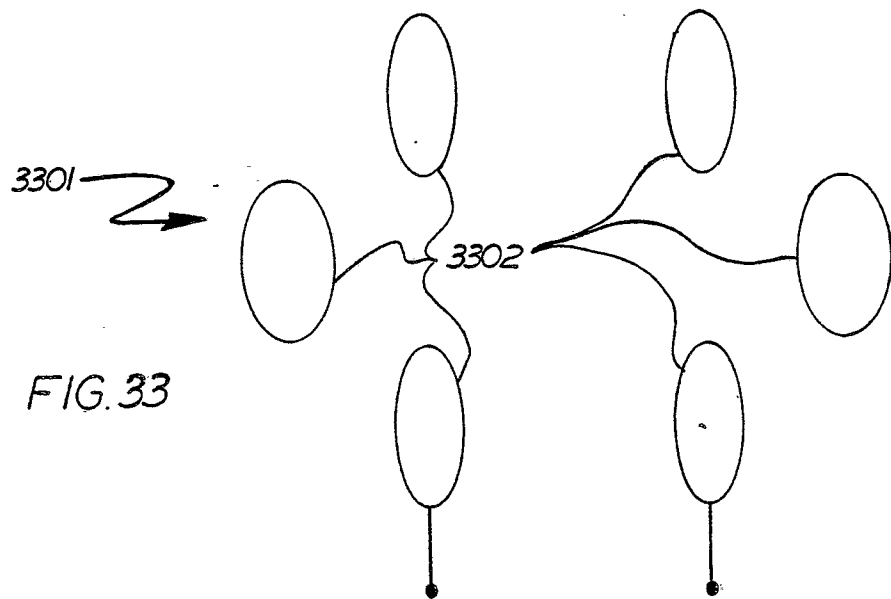


FIG. 33

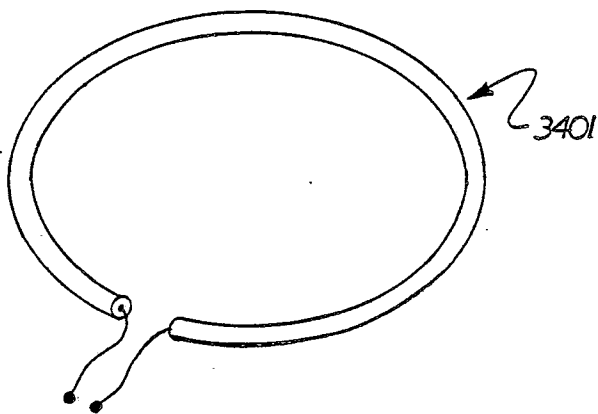


FIG. 34



DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl. ³)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	US - A - 1 803 620 (S.M. JESTER) * fig. 1 to 3 *	1,2	H 01 Q 11/08
	DE - C - 443 959 (A. TAYLOR) * page 5, column 1, line 7 and the following; fig. 6 *	1-6	
	US - A - 4 014 028 (J.A. CONE et al.) * fig. 1 *	9	TECHNICAL FIELDS SEARCHED (Int. Cl. ³)
A	US - A - 3 235 805 (D.L. HINGS) * fig. 1 to 23 *		H 01 Q 1/00 H 01 Q 9/00 H 01 Q 11/00
A	US - A - 3 122 747 (H.O. HEISRATH) * fig. 1 to 4 *		
A	US - A - 1 615 755 (F. GRAUE) * fig. 1 *		
A	DE - B - 1 129 191 (SIEMENS) * fig. 1 to 4 *		CATEGORY OF CITED DOCUMENTS
	DE - U - 1 751 249 (J. HOLDER) * claim 9; fig. 9 *		X: particularly relevant A: technological background O: non-written disclosure P: intermediate document T: theory or principle underlying the invention E: conflicting application D: document cited in the application L: citation for other reasons
A	DE - C - 864 707 (H. SCHIEREN) * fig. 1 to 5 *		&: member of the same patent family, corresponding document
☒ The present search report has been drawn up for all claims			
Place of search Berlin		Date of completion of the search 18-09-1981	Examiner BREUSING