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(54) **EXCITATION AND USE OF GUIDED SURFACE WAVE MODES ON LOSSY MEDIA**

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Publication Classification

(57) **ABSTRACT**

Disclosed are various embodiments systems and methods for transmission and reception of electrical energy along a surface of a terrestrial medium. A polyphase waveguide probe that transmits electrical energy in the form of a guided surface wave along a surface of a terrestrial medium. A receive circuit is used to receive the electrical energy.

FIG. 1

FIG. 2

$$D_1 = H_1 + d/2 + d/2 = H_1 + d$$

$$D_2 = H_2 + d/2 + d/2 = H_2 + d$$
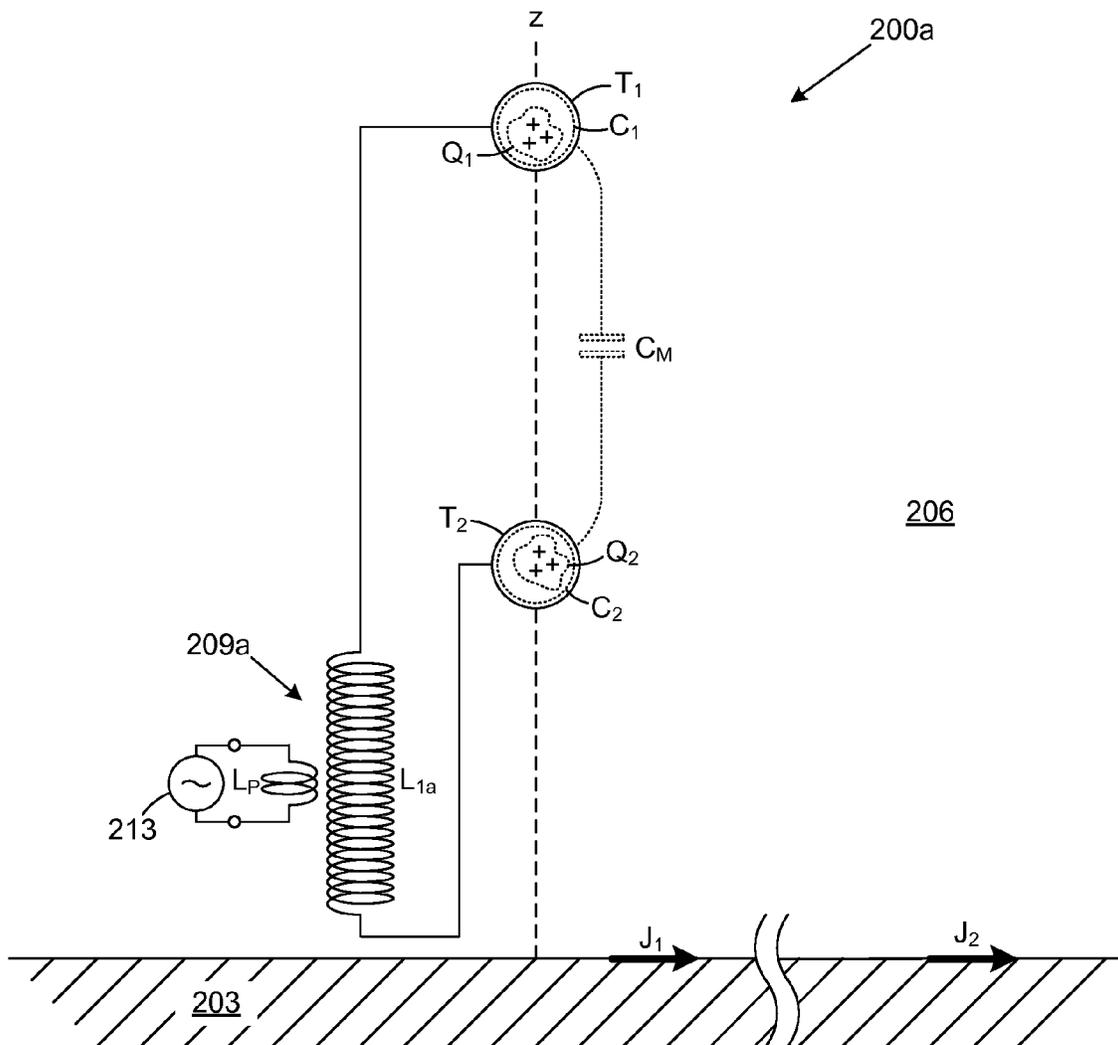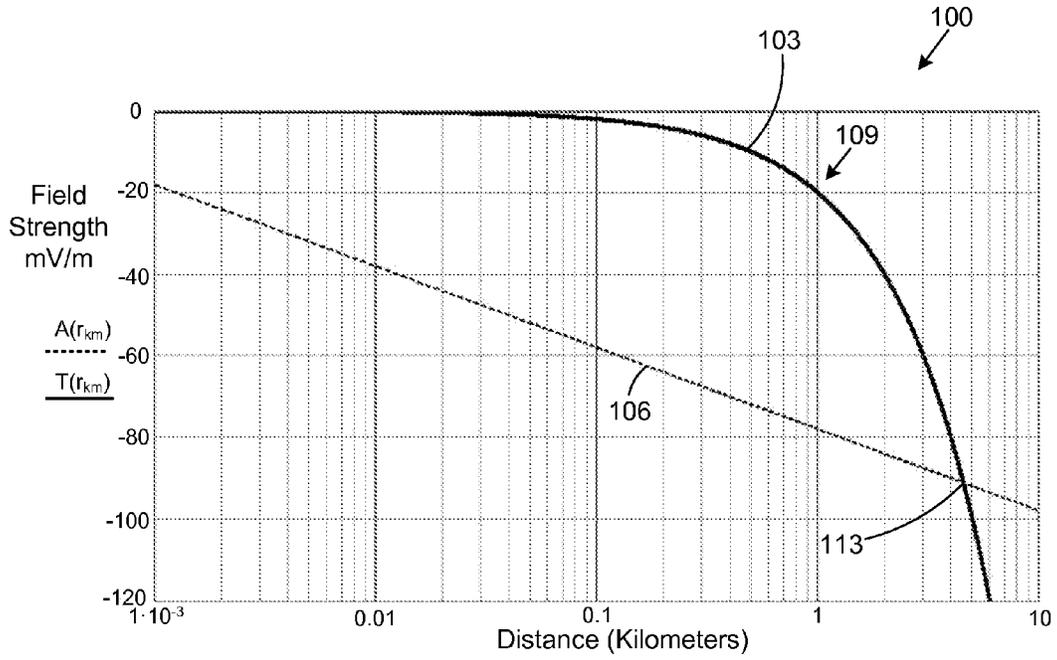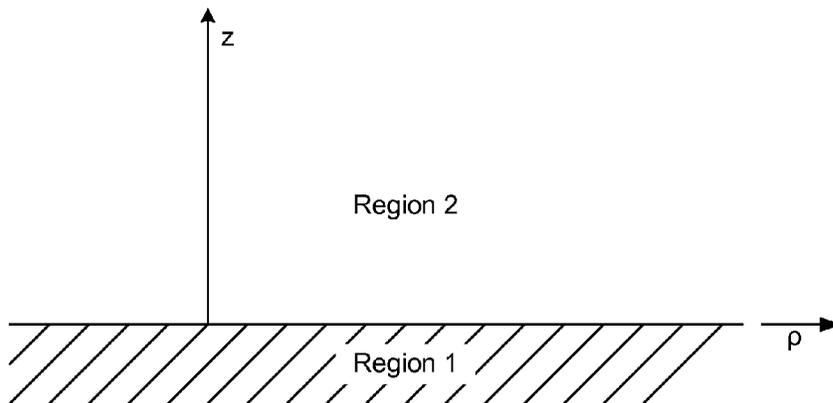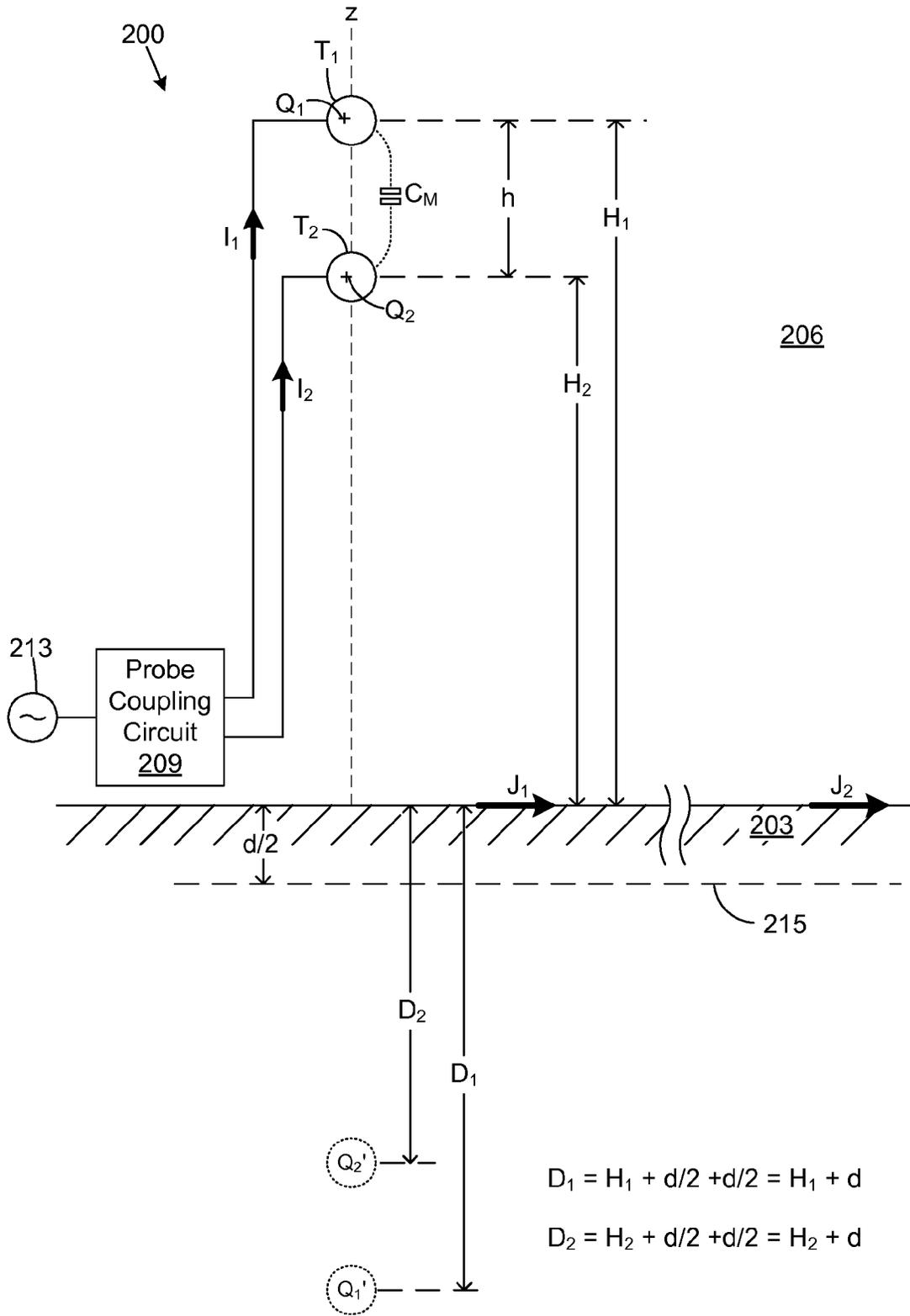
FIG. 3

$$P_0: \quad \left| J_{P_0} \right| \angle \varphi_0$$

$$P_1: \quad \left| J_{P_1} \right| \angle \varphi_0 - \beta R_1$$

$$P_2: \quad \left| J_{P_2} \right| \angle \varphi_0 - \beta R_2 + \varphi_\Delta$$
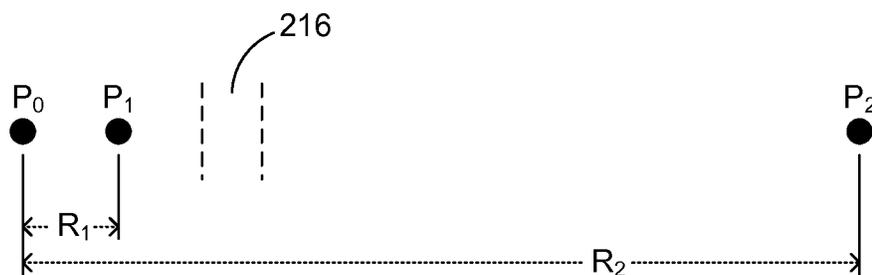
$$\varphi_\Delta = \arg\left(\sqrt{\gamma}\right) \approx \frac{\pi}{4}$$

FIG. 4
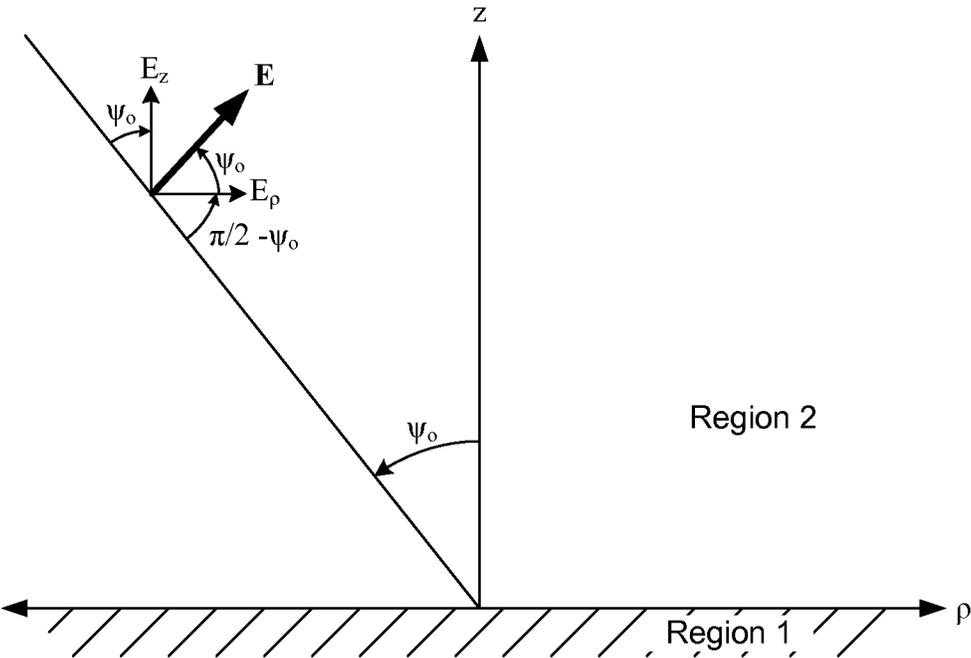
FIG. 5
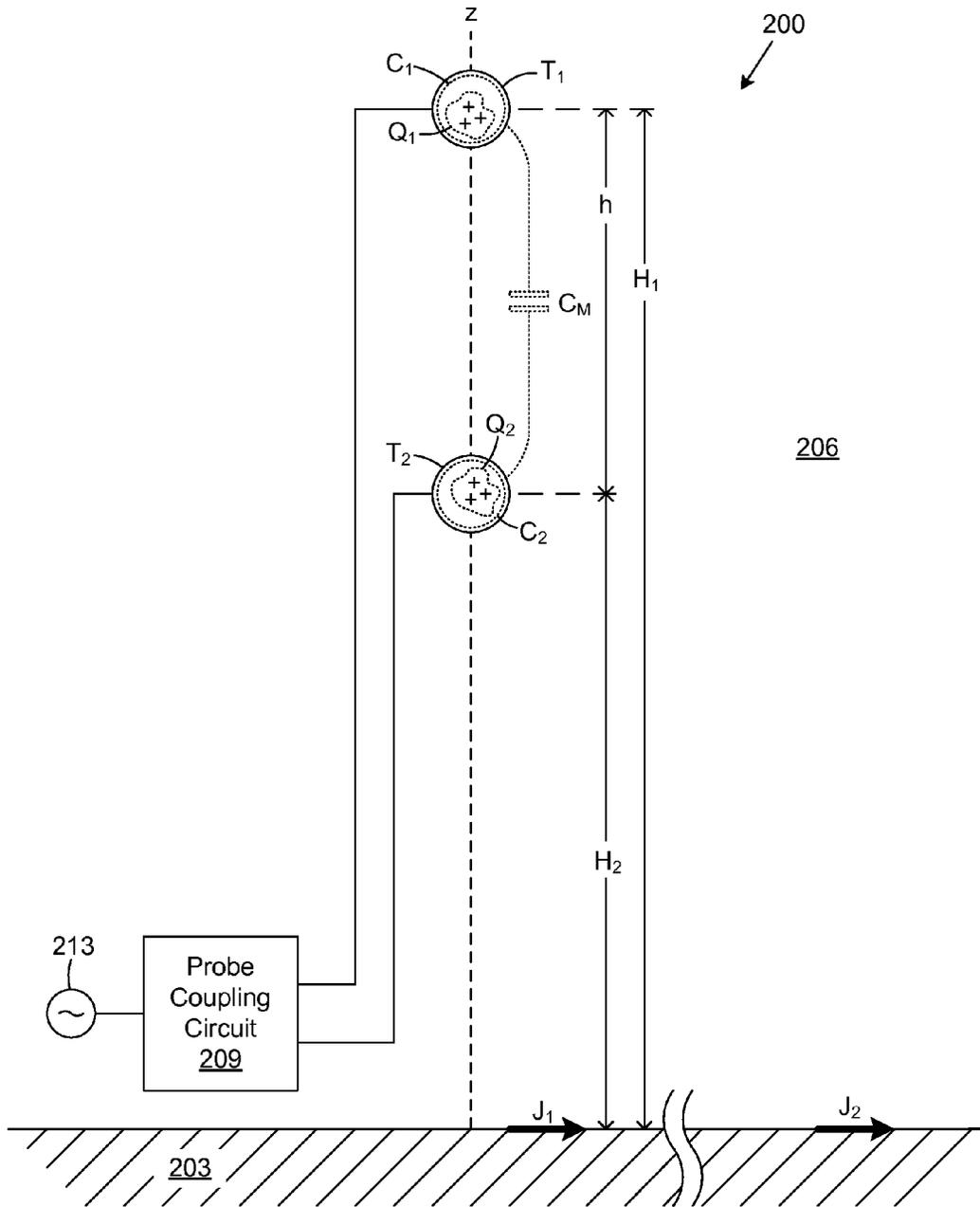
FIG. 6
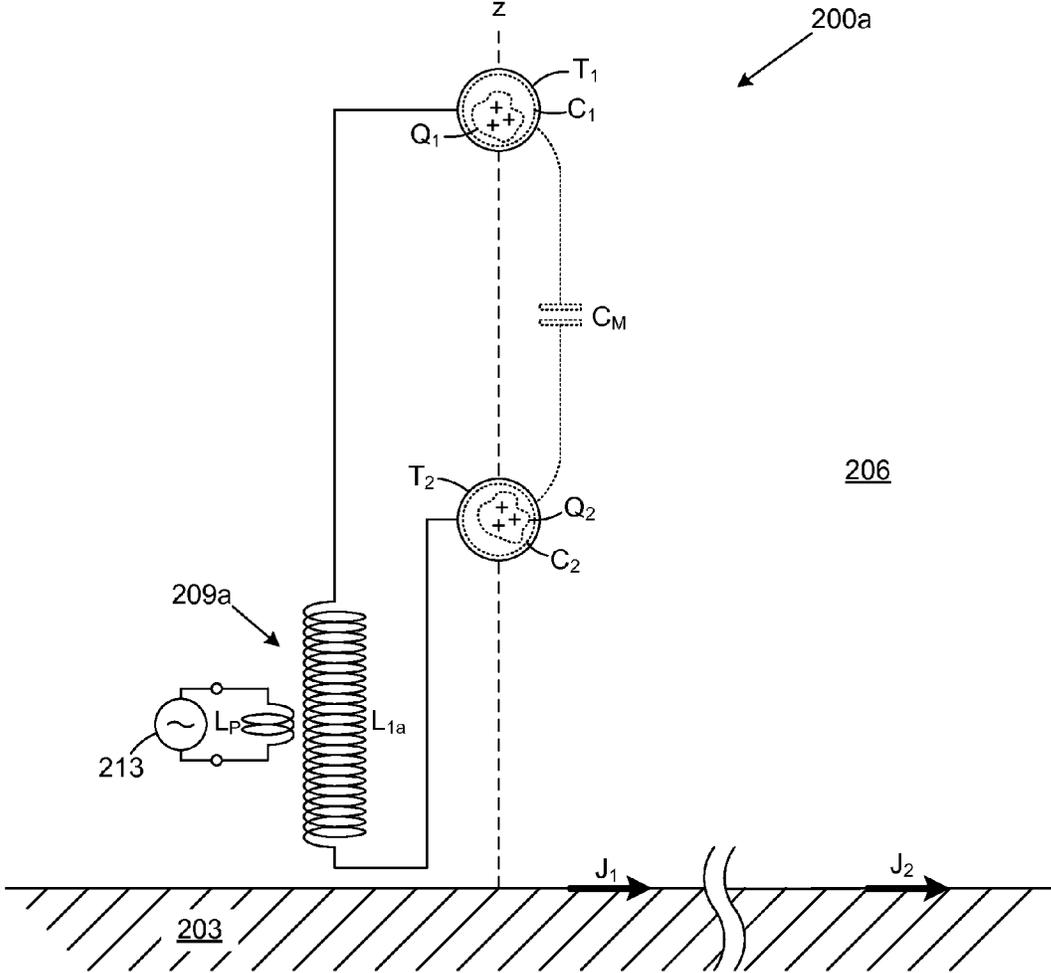
FIG. 7A
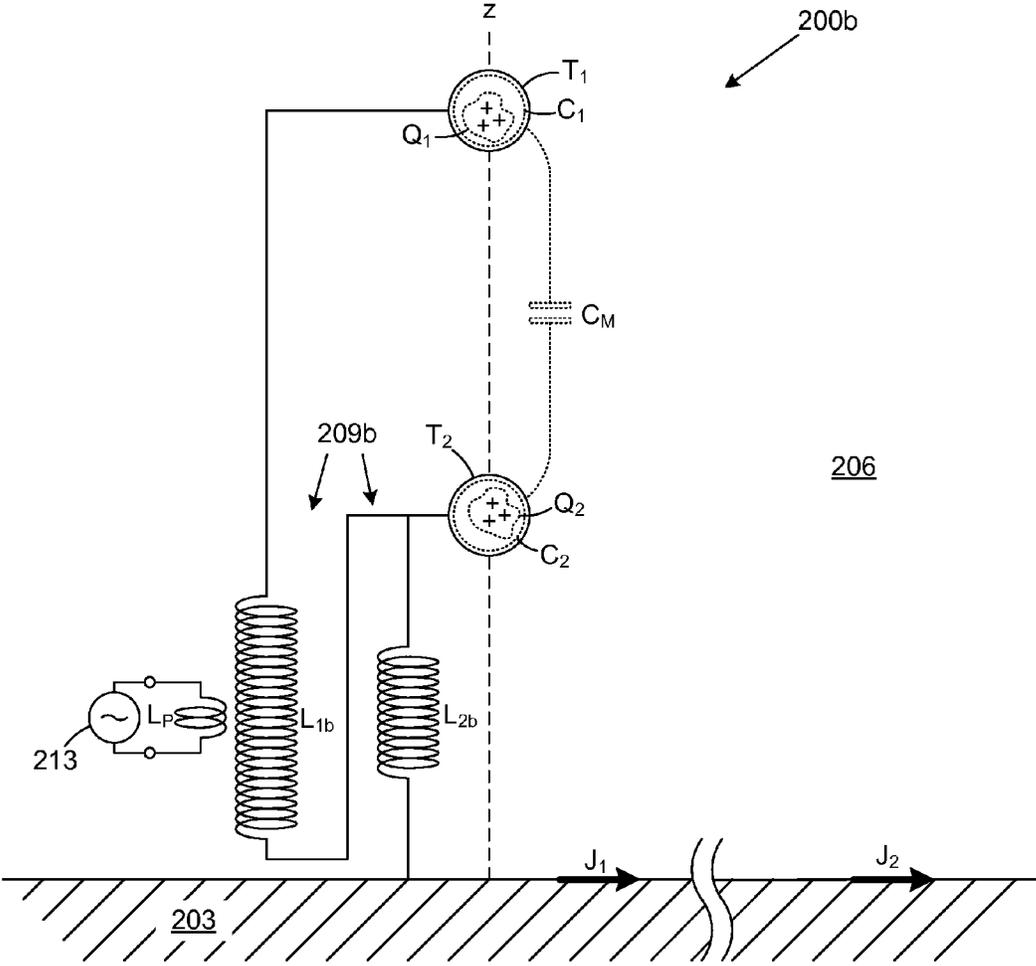
FIG. 7B
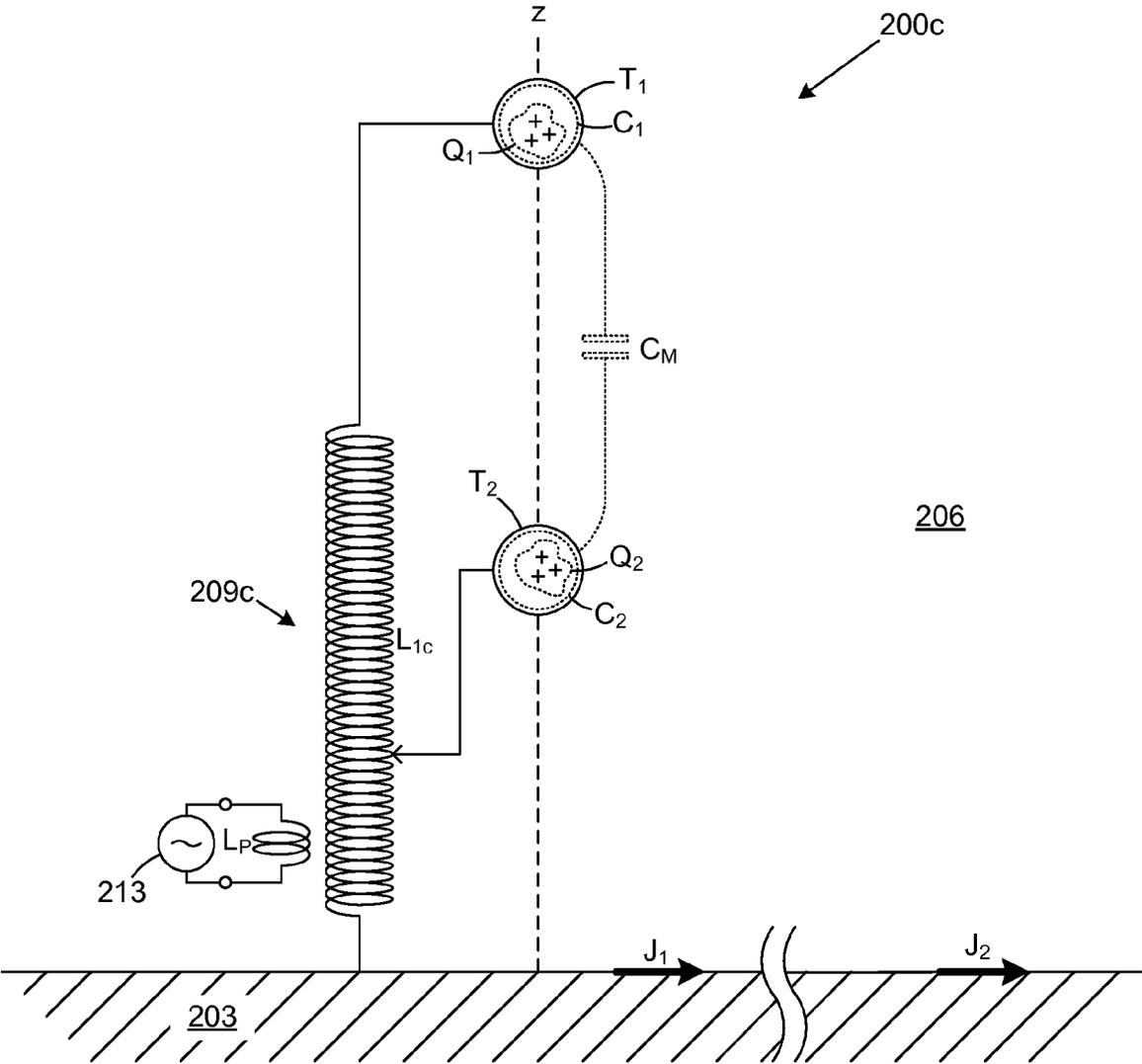
FIG. 7C
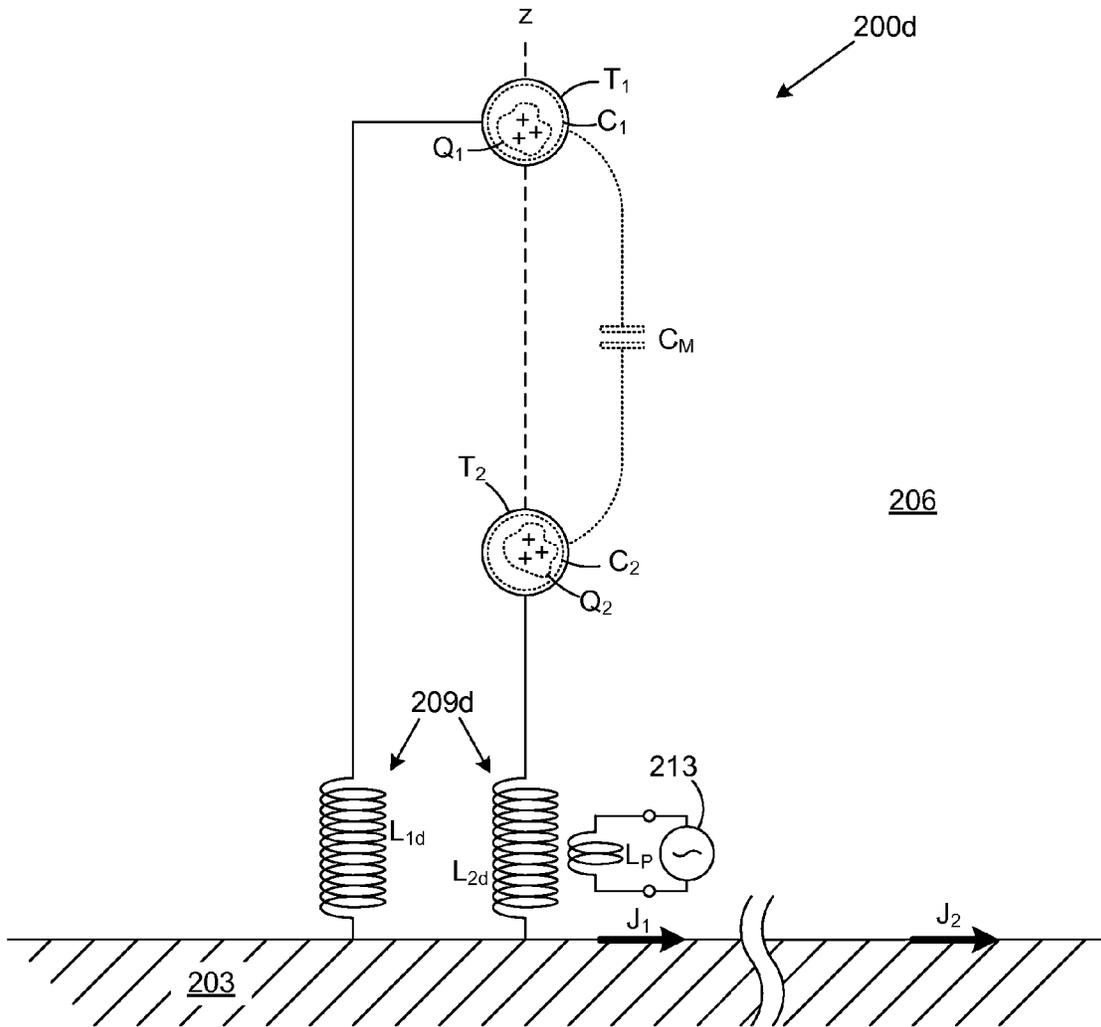
FIG. 7D
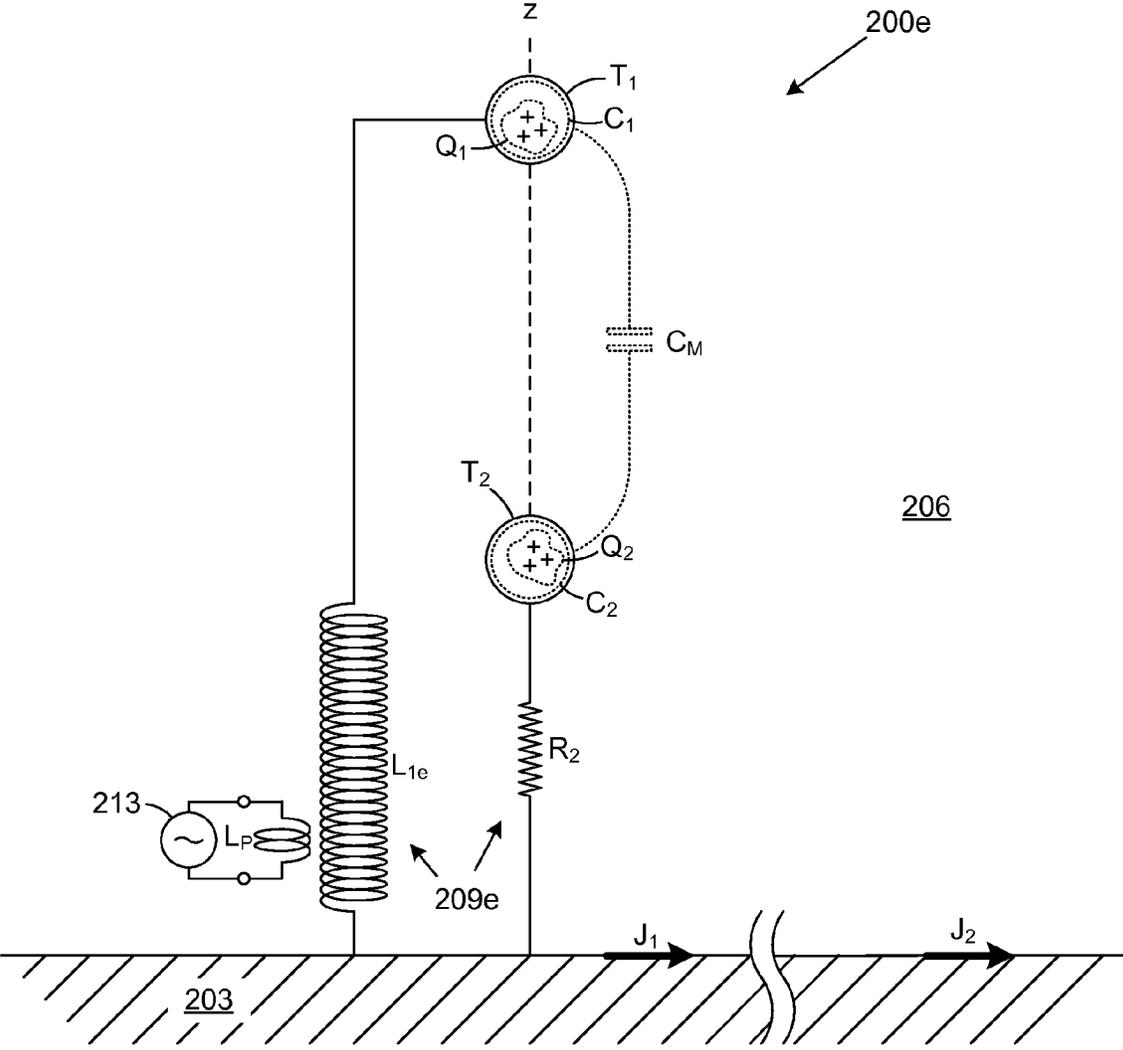
FIG. 7E
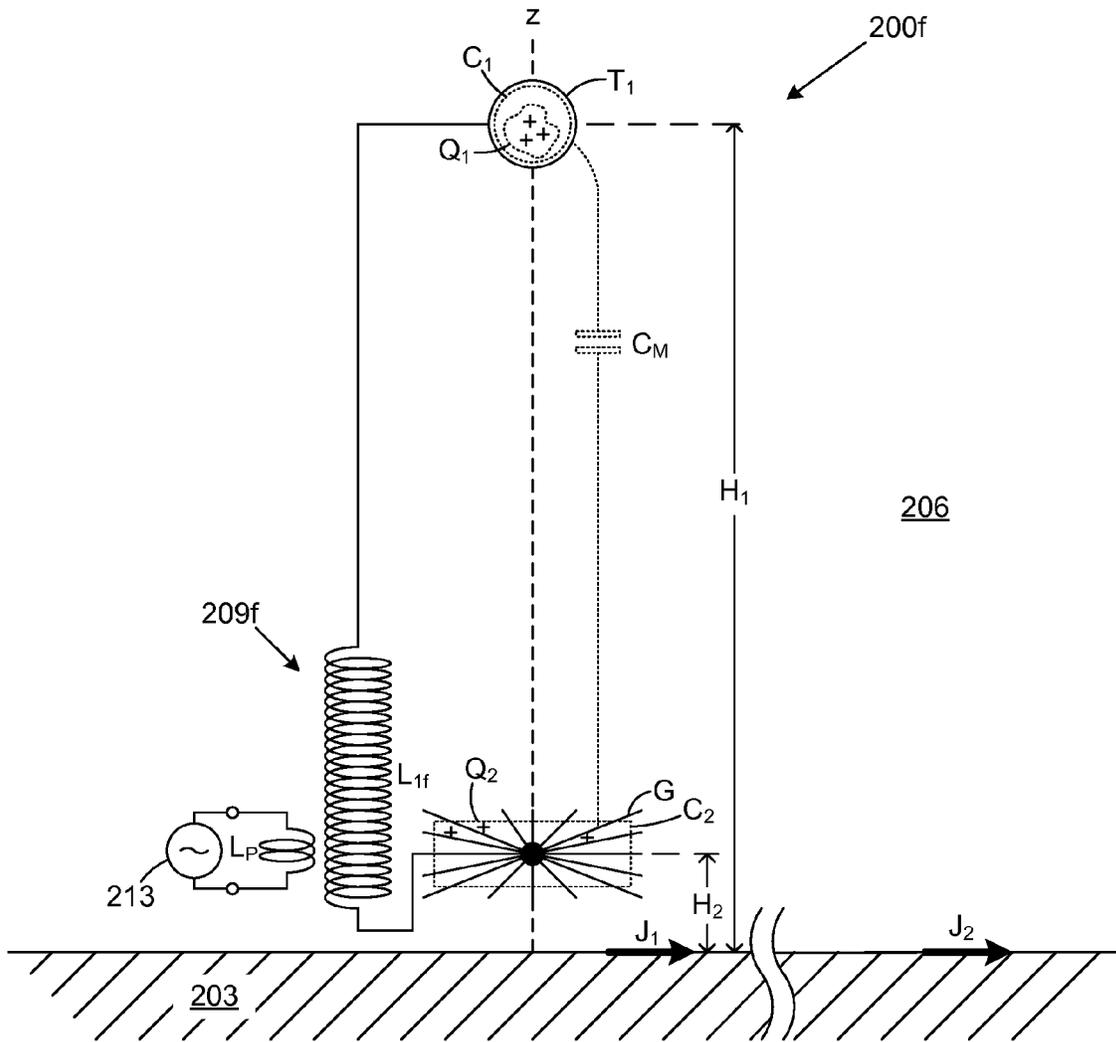
FIG. 7F

FIG. 7G

FIG. 7H

FIG. 7I

FIG. 7J

300a

FIG. 8A

300b
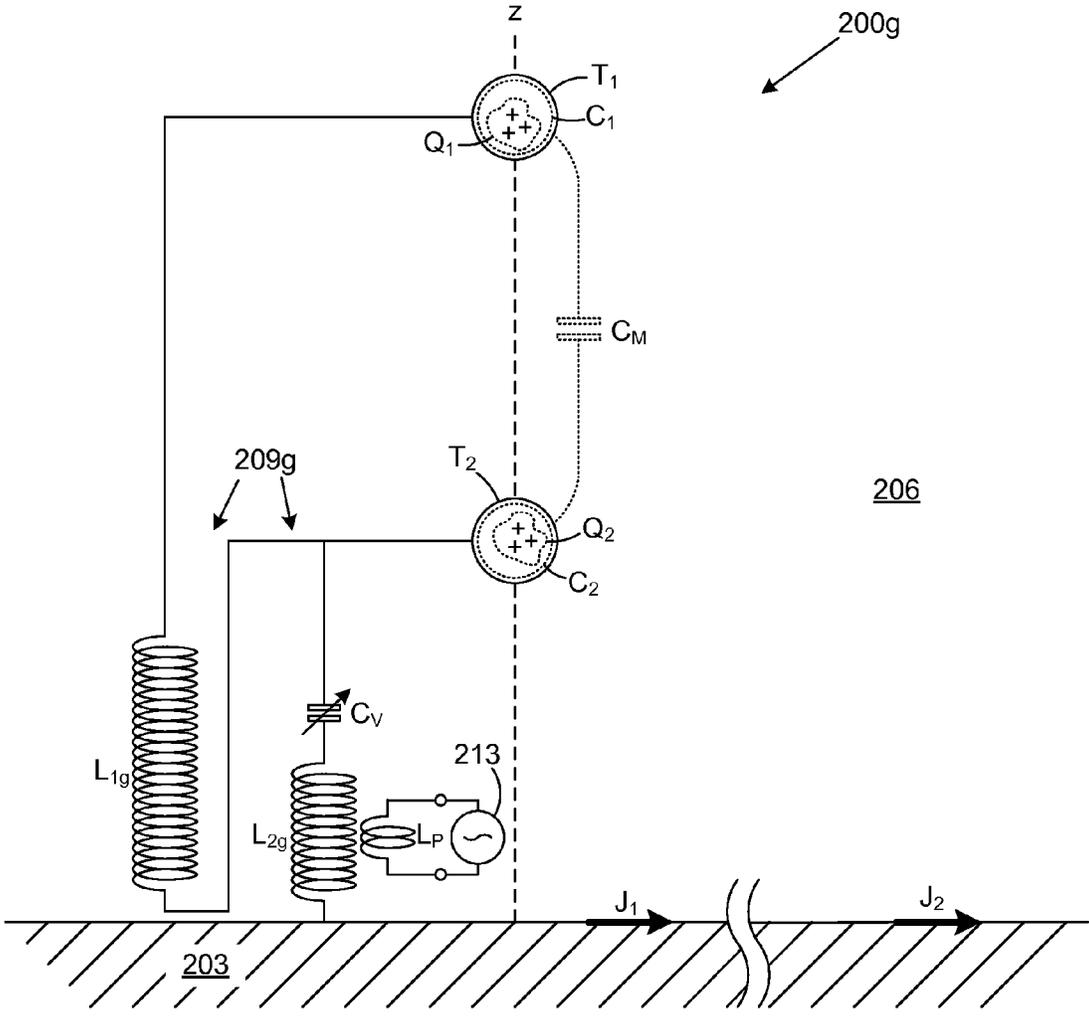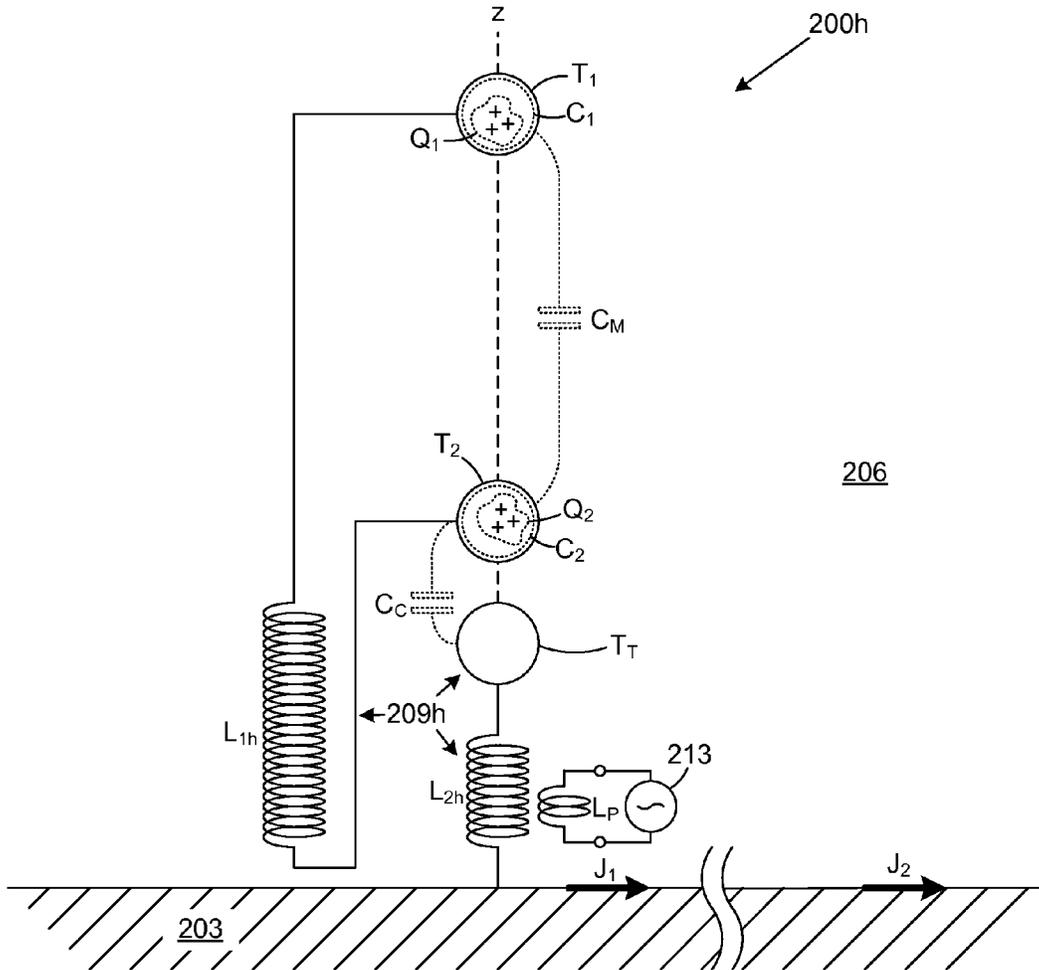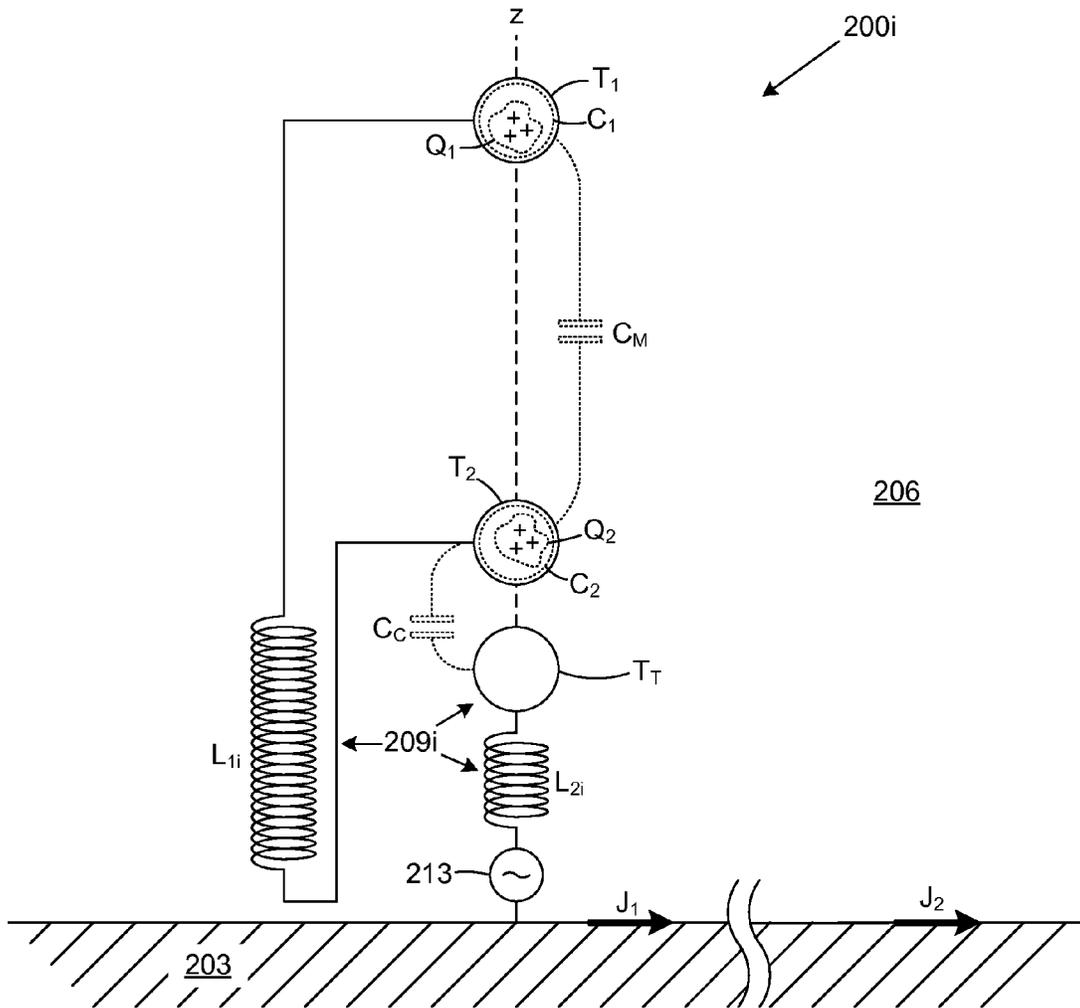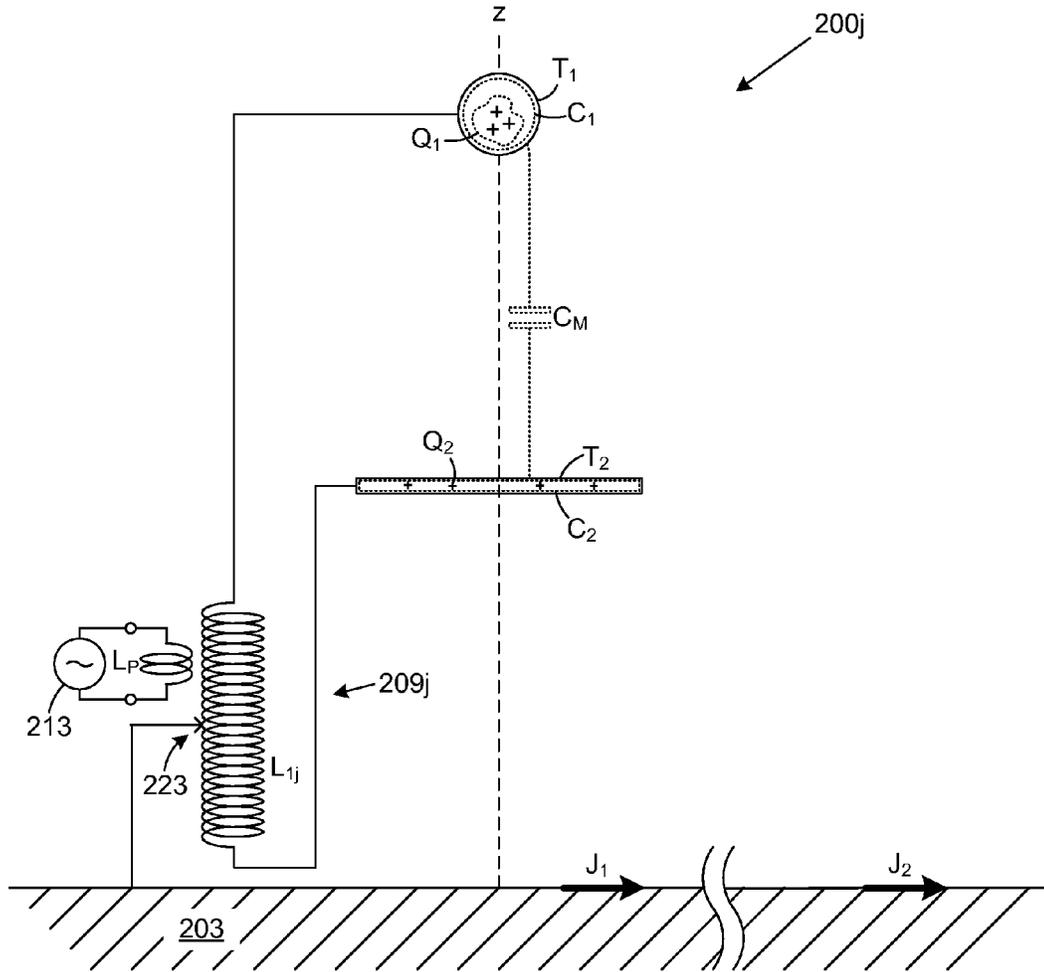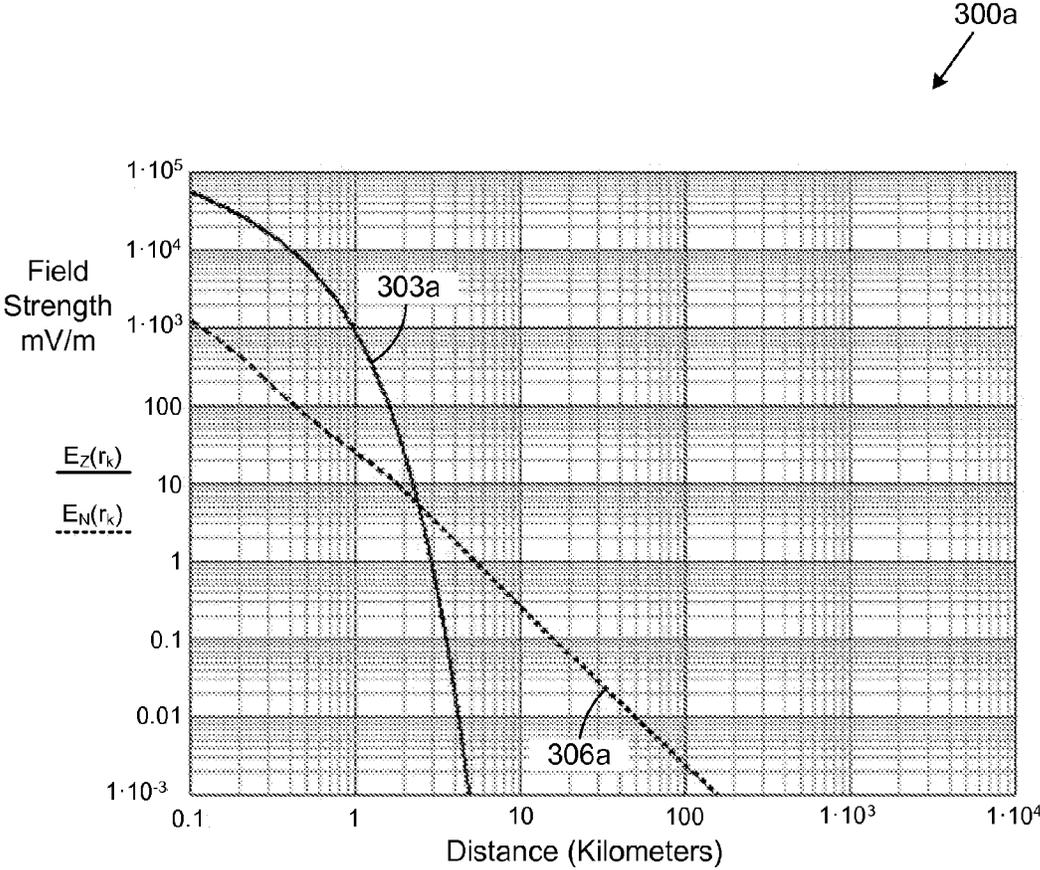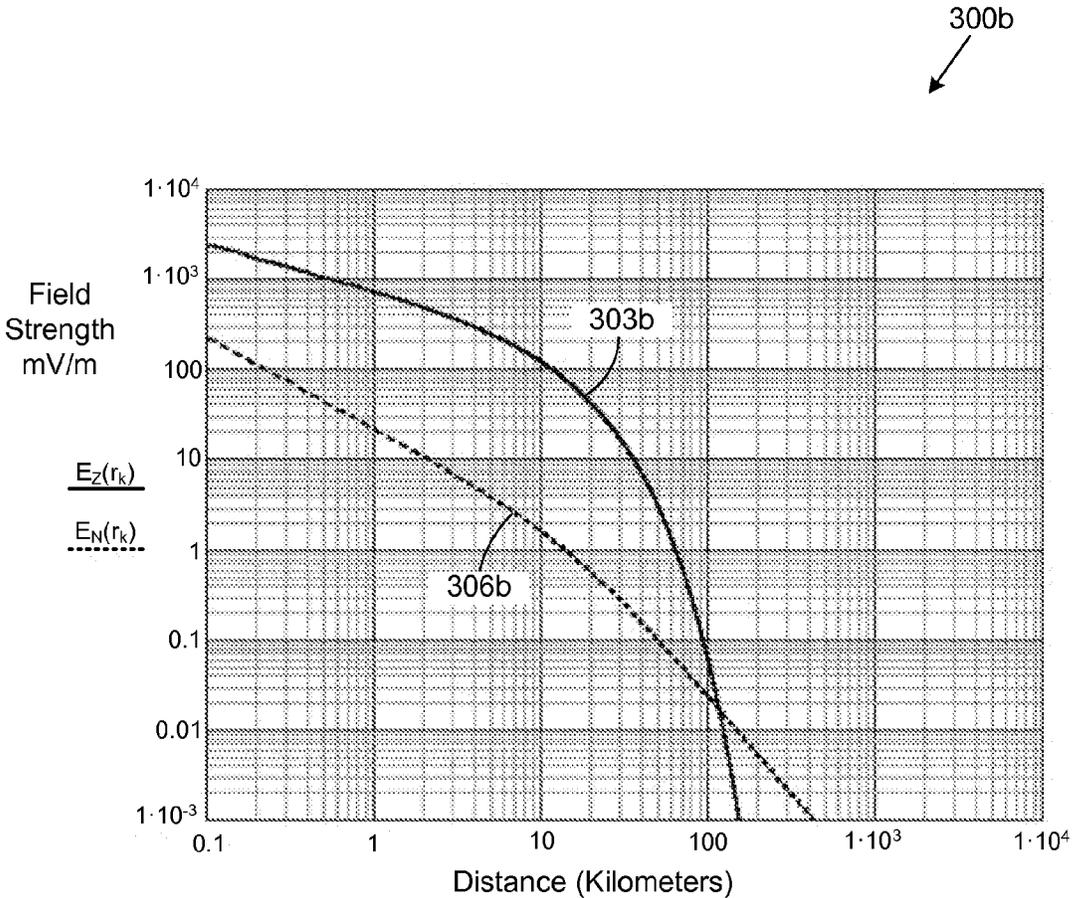
FIG. 8B

FIG. 8C

FIG. 9

FIG. 10

FIG. 11

703

FIG. 12A

713

Impedance
Matching
Network
719

Electric
Load
716

203

T_R

C_R

706

721

L_R

L_S

Impedance
Matching
Network
723

Electric
Load
726

FIG. 12B

203

709

729

Impedance
Matching
Network
733

Electric
Load
736
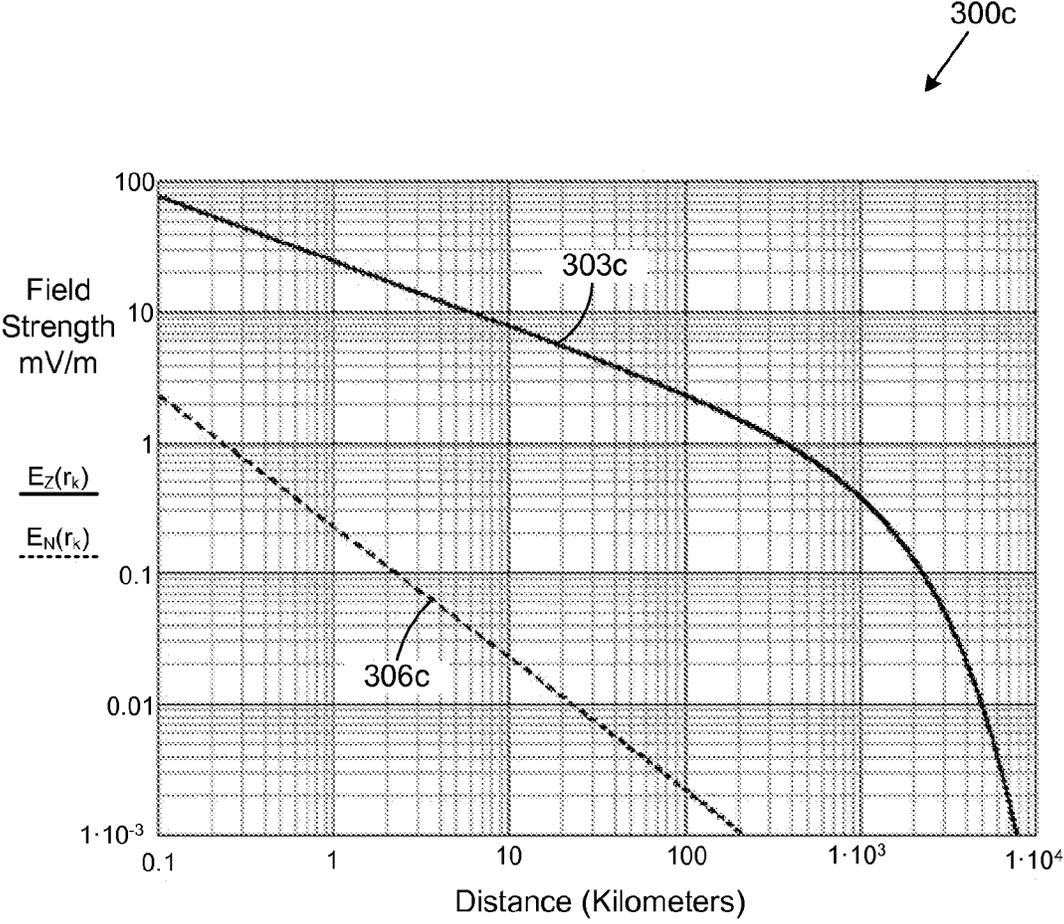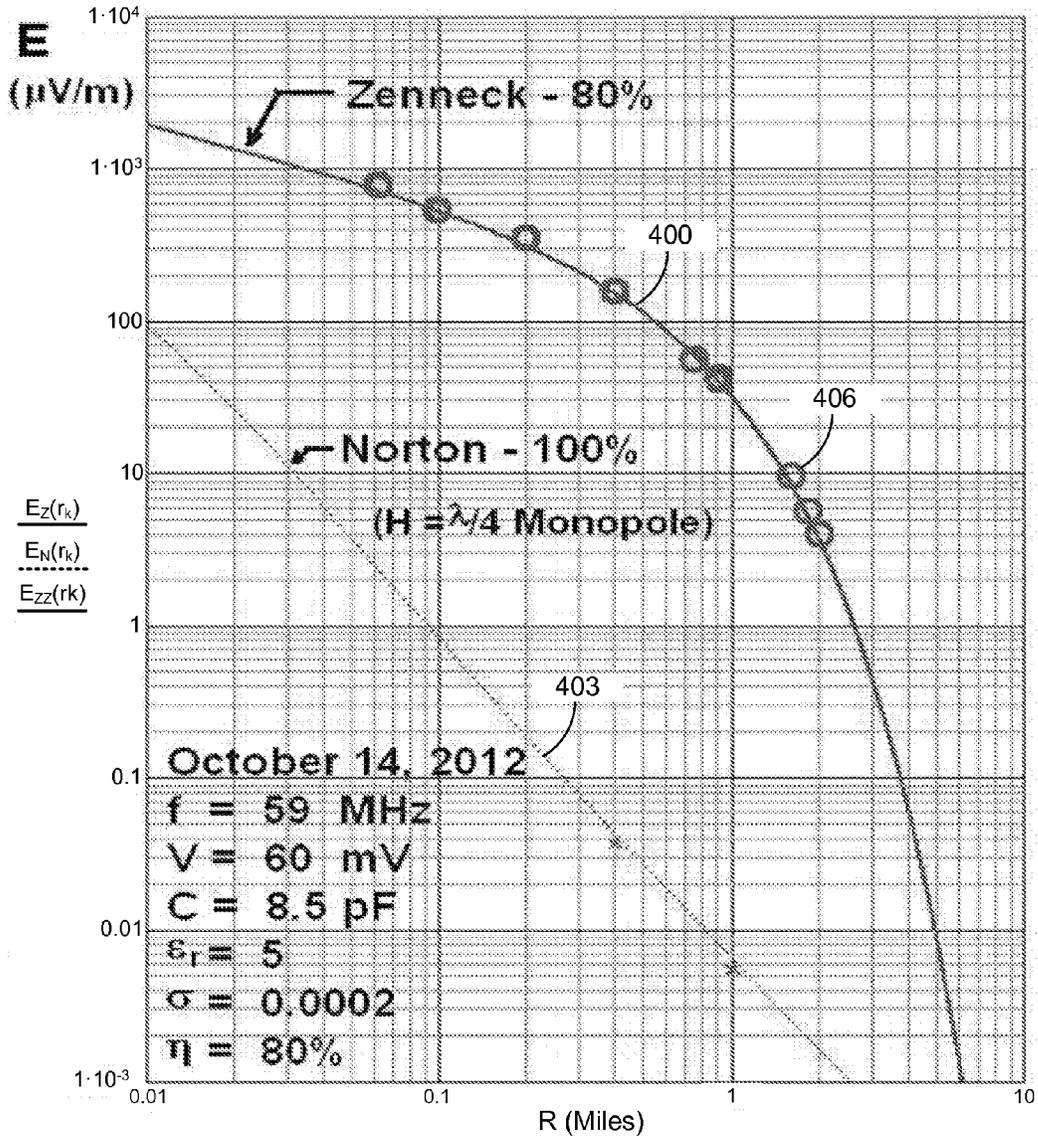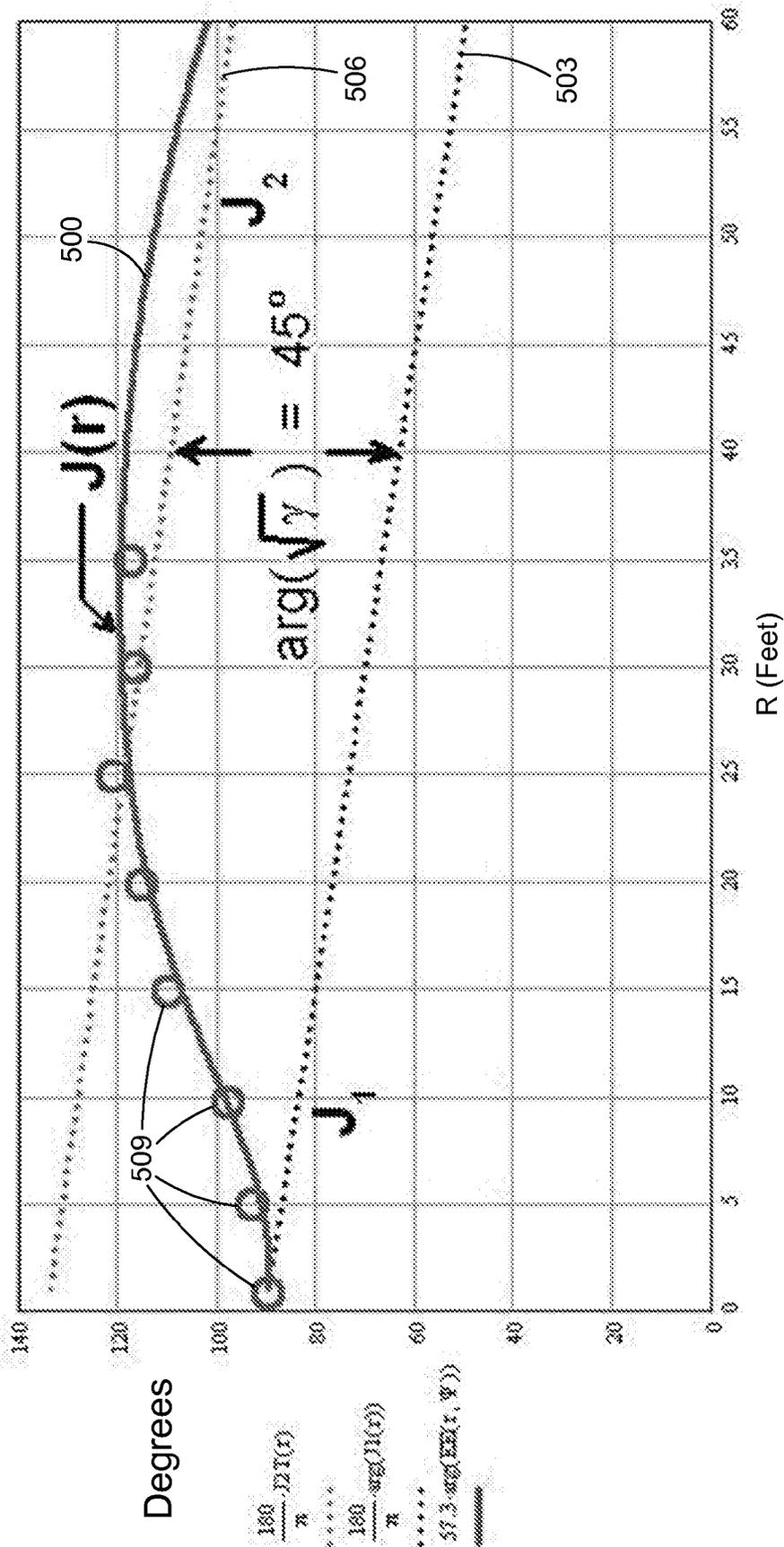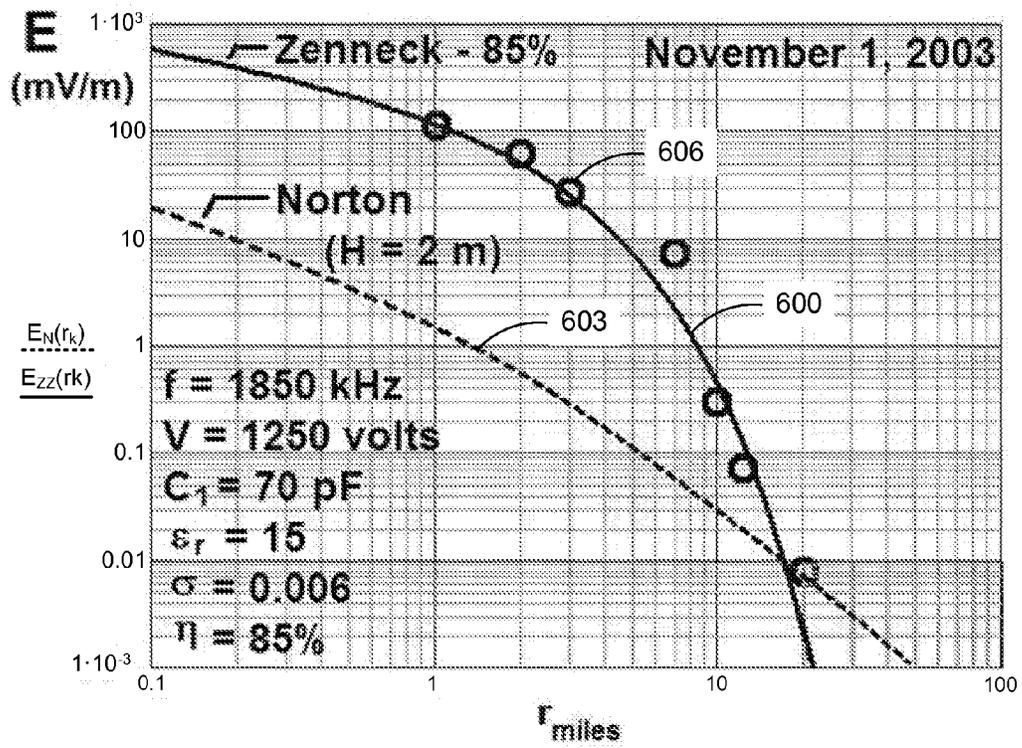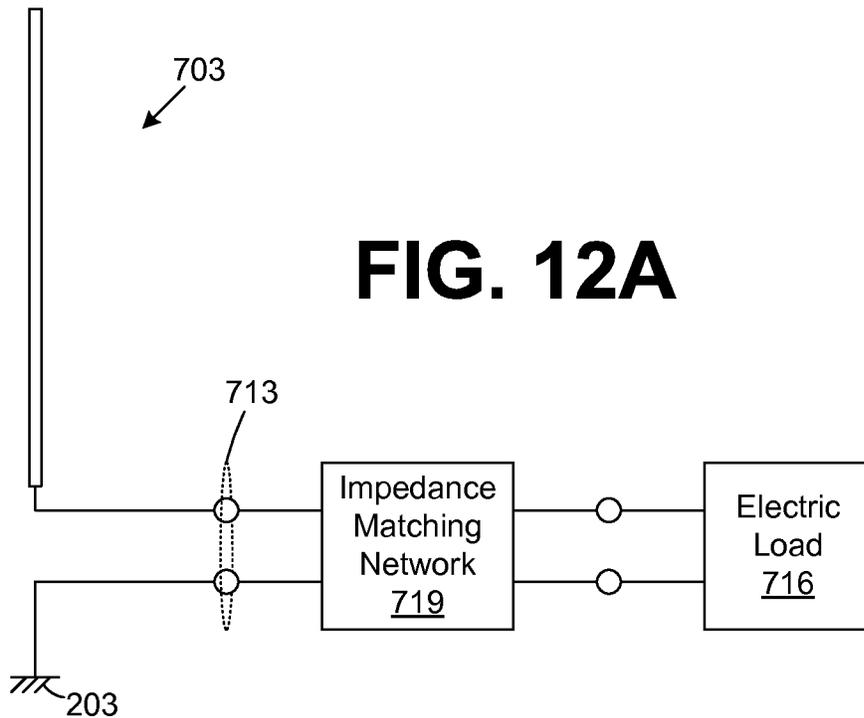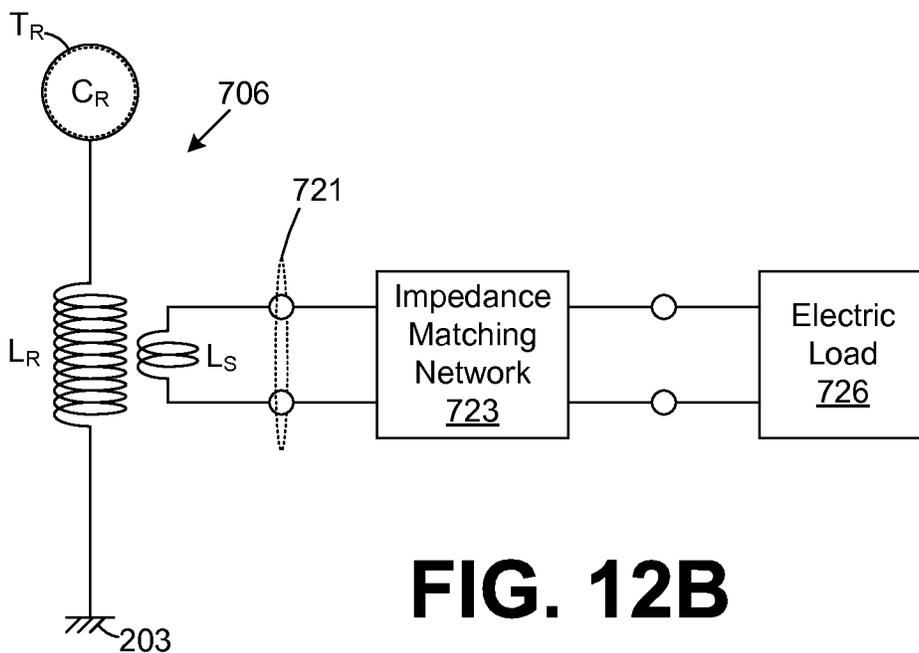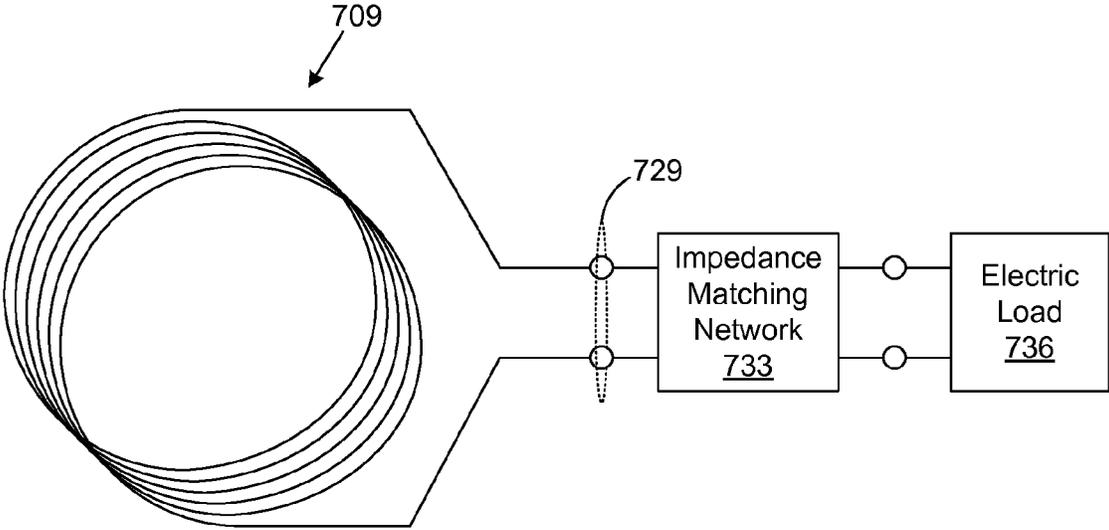
FIG. 13
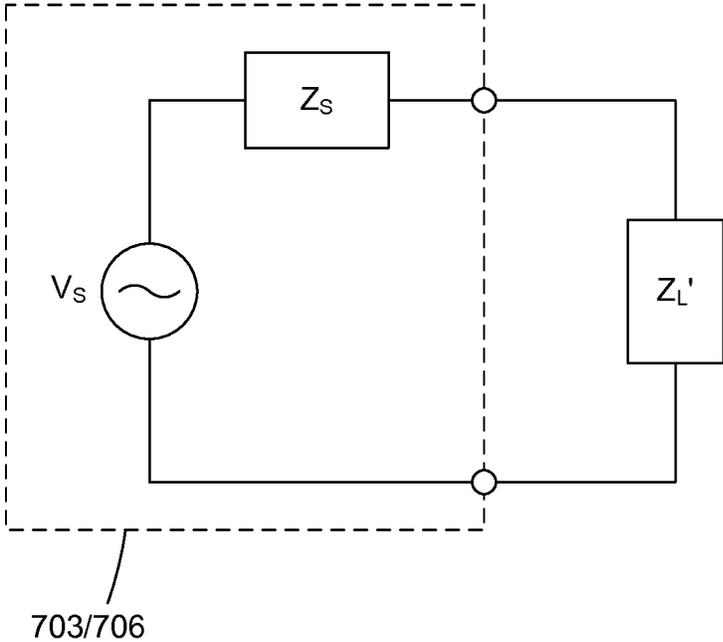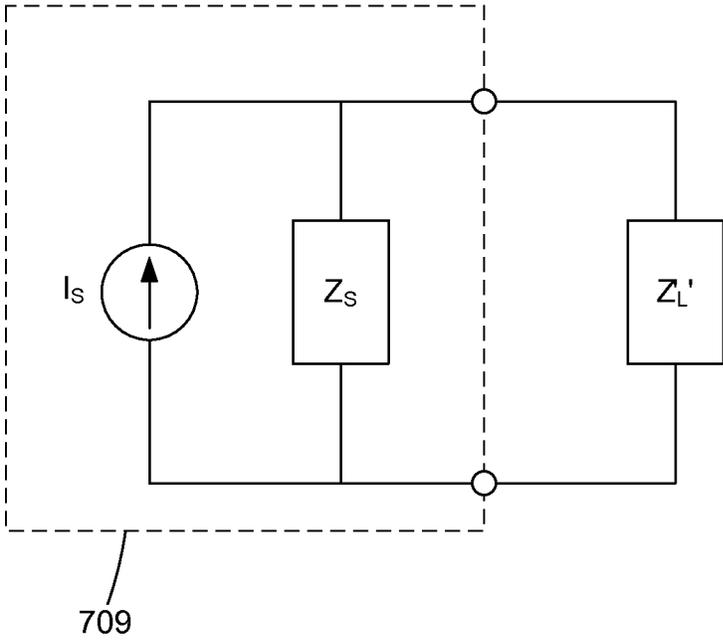
FIG. 14A

FIG. 14B

EXCITATION AND USE OF GUIDED SURFACE WAVE MODES ON LOSSY MEDIA

BACKGROUND

[0001] For over a century, signals transmitted by radio waves involved radiation fields launched using conventional antenna structures. In contrast to radio science, electrical power distribution systems in the last century involved the transmission of energy guided along electrical conductors. This understanding of the distinction between radio frequency (RF) and power transmission has existed since the early 1900's.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0003] FIG. 1 is a chart that depicts a field strength as a function of distance for a guided electromagnetic field and a radiated electromagnetic field.

[0004] FIG. 2 is a drawing that illustrates a propagation interface with two regions employed for transmission of a guided surface wave according to various embodiments of the present disclosure.

[0005] FIG. 3 is a drawing that illustrates a polyphase waveguide probe disposed with respect to a propagation interface of FIG. 2 according to an embodiment of the present disclosure.

[0006] FIG. 4 is a drawing that provides one example illustration of a phase shift in a ground current that facilitates the launching of a guided surface-waveguide mode on a lossy conducting medium in the propagation interface of FIG. 3 according to an embodiment of the present disclosure.

[0007] FIG. 5 is a drawing that illustrates a complex angle of insertion of an electric field synthesized by the polyphase waveguide probes according to the various embodiments of the present disclosure.

[0008] FIG. 6 is a schematic of a polyphase waveguide probe according to an embodiment of the present disclosure.

[0009] FIGS. 7A-J are schematics of specific examples of the polyphase waveguide probe of FIG. 6 according to various embodiments of the present disclosure.

[0010] FIGS. 8A-C are graphs that illustrate field strengths of guided surface waves at select transmission frequencies generated by the various embodiments of polyphase waveguide probes according to the various embodiments of the present disclosure.

[0011] FIG. 9 shows one example of a graph of experimental measurements of field strength of a guided surface wave at 59 Megahertz as a function of distance generated by a polyphase waveguide probe according to an embodiment of the present disclosure.

[0012] FIG. 10 shows a graph of experimental measurements of the phase as a function of distance of the guided surface wave of FIG. 9 according to an embodiment of the present disclosure.

[0013] FIG. 11 shows another example of a graph of experimental measurements of field strength as a function of distance of a guided surface wave generated by a polyphase waveguide probe at 1.85 Megahertz according to an embodiment of the present disclosure.

[0014] FIGS. 12A-B depict examples of receivers that may be employed to receive energy transmitted in the form of a guided surface wave launched by a polyphase waveguide probe according to the various embodiments of the present disclosure.

[0015] FIG. 13 depicts an example of an additional receiver that may be employed to receive energy transmitted in the form of a guided surface wave launched by a polyphase waveguide probe according to the various embodiments of the present disclosure.

[0016] FIG. 14A depicts a schematic diagram representing the Thevenin-equivalent of the receivers depicted in FIGS. 12A-B according to an embodiment of the present disclosure.

[0017] FIG. 14B depicts a schematic diagram representing the Norton-equivalent of the receiver depicted in FIG. 13 according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0018] Referring to FIG. 1, to begin, some terminology shall be established to provide clarity in the discussion of concepts to follow. First, as contemplated herein, a formal distinction is drawn between radiated electromagnetic fields and guided electromagnetic fields.

[0019] As contemplated herein, a radiated electromagnetic field comprises electromagnetic energy that is emitted from a source structure in the form of waves that are not bound to a waveguide. For example, a radiated electromagnetic field is generally a field that leaves an electric structure such as an antenna and propagates through the atmosphere or other medium and is not bound to any waveguide structure. Once radiated electromagnetic waves leave an electric structure such as an antenna, they continue to propagate in the medium of propagation (such as air) independent of their source until they dissipate regardless of whether the source continues to operate. Once electromagnetic waves are radiated, they are not recoverable unless intercepted, and, if not intercepted, the energy inherent in radiated electromagnetic waves is lost forever. Electrical structures such as antennas are designed to radiate electromagnetic fields by maximizing the ratio of the radiation resistance to the structure loss resistance. Radiated energy spreads out in space and is lost regardless of whether a receiver is present. The energy density of radiated fields is a function of distance due to geometrical spreading. Accordingly, the term "radiate" in all its forms as used herein refers to this form of electromagnetic propagation.

[0020] A guided electromagnetic field is a propagating electromagnetic wave whose energy is concentrated within or near boundaries between media having different electromagnetic properties. In this sense, a guided electromagnetic field is one that is bound to a waveguide and may be characterized as being conveyed by the current flowing in the waveguide. If there is no load to receive and/or dissipate the energy conveyed in a guided electromagnetic wave, then no energy is lost except for that dissipated in the conductivity of the guiding medium. Stated another way, if there is no load for a guided electromagnetic wave, then no energy is consumed. Thus, a generator or other source generating a guided electromagnetic field does not deliver real power unless a resistive load is present. To this end, such a generator or other source essentially runs idle until a load is presented. This is akin to running a generator to generate a 60 Hertz electromagnetic wave that is transmitted over power lines where there is no

electrical load. It should be noted that a guided electromagnetic field or wave is the equivalent to what is termed a "transmission line mode." This contrasts with radiated electromagnetic waves in which real power is supplied at all times in order to generate radiated waves. Unlike radiated electromagnetic waves, guided electromagnetic energy does not continue to propagate along a finite length waveguide after the energy source is turned off. Accordingly, the term "guide" in all its forms as used herein refers to this transmission mode of electromagnetic propagation.

[0021] To further illustrate the distinction between radiated and guided electromagnetic fields, reference is made to FIG. 1 that depicts graph **100** of field strength in decibels (dB) above an arbitrary reference in volts per meter as a function of distance in kilometers on a log-dB plot. The graph **100** of FIG. 1 depicts a guided field strength curve **103** that shows the field strength of a guided electromagnetic field as a function of distance. This guided field strength curve **103** is essentially the same as a transmission line mode. Also, the graph **100** of FIG. 1 depicts a radiated field strength curve **106** that shows the field strength of a radiated electromagnetic field as a function of distance.

[0022] Of interest are the shapes of the curves **103/106** for radiation and for guided wave propagation. The radiated field strength curve **106** falls off geometrically (1/d, where d is distance) and is a straight line on the log-log scale. The guided field strength curve **103**, on the other hand, has the characteristic exponential decay of $e^{-\alpha d}/\sqrt{d}$ and exhibits a distinctive knee **109**. Thus, as shown, the field strength of a guided electromagnetic field falls off at a rate of $e^{-\alpha d}/\sqrt{d}$, whereas the field strength of a radiated electromagnetic field falls off at a rate of 1/d, where d is the distance. Due to the fact that the guided field strength curve **103** falls off exponentially, the guided field strength curve **103** features the knee **109** as mentioned above. The guided field strength curve **103** and the radiated field strength curve **106** intersect at a crossover point **113** which occurs at a crossover distance. At distances less than the crossover distance, the field strength of a guided electromagnetic field is significantly greater at most locations than the field strength of a radiated electromagnetic field. At distances greater than the crossover distance, the opposite is true. Thus, the guided and radiated field strength curves **103** and **106** further illustrate the fundamental propagation difference between guided and radiated electromagnetic fields. For an informal discussion of the difference between guided and radiated electromagnetic fields, reference is made to Milligan, T., *Modern Antenna Design*, McGraw-Hill, 1st Edition, 1985, pp. 8-9, which is incorporated herein by reference in its entirety.

[0023] The distinction between radiated and guided electromagnetic waves, made above, is readily expressed formally and placed on a rigorous basis. That two such diverse solutions could emerge from one and the same linear partial differential equation, the wave equation, analytically follows from the boundary conditions imposed on the problem. The Green function for the wave equation, itself, contains the distinction between the nature of radiation and guided waves.

[0024] In empty space, the wave equation is a differential operator whose eigenfunctions possess a continuous spectrum of eigenvalues on the complex wave-number plane. This transverse electro-magnetic (TEM) field is called the radiation field, and those propagating fields are called "Hertzian waves". However, in the presence of a conducting boundary, the wave equation plus boundary conditions mathematically lead to a spectral representation of wave-numbers composed of a continuous spectrum plus a sum of discrete spectra. To this end, reference is made to Sommerfeld, A., "Uber die Ausbreitung der Wellen in der Drahtlosen Telegraphie," Annalen der Physik, Vol. 28, 1909, pp. 665-736. Also see Sommerfeld, A., "Problems of Radio," published as Chapter 6 in *Partial Differential Equations in Physics—Lectures on Theoretical Physics: Volume VI*, Academic Press, 1949, pp. 236-289, 295-296; Collin, R. E., "Hertzian Dipole Radiating Over a Lossy Earth or Sea: Some Early and Late 20th Century Controversies," *IEEE Antennas and Propagation Magazine*, Vol. 46, No. 2, April 2004, pp. 64-79; and Reich, H. J., Ordnung, P. F, Krauss, H. L., and Skalnik, J. G., *Microwave Theory and Techniques*, Van Nostrand, 1953, pp. 291-293, each of these references being incorporated herein by reference in their entirety.

[0025] To summarize the above, first, the continuous part of the wave-number eigenvalue spectrum, corresponding to branch-cut integrals, produces the radiation field, and second, the discrete spectra, and corresponding residue sum arising from the poles enclosed by the contour of integration, result in non-TEM traveling surface waves that are exponentially damped in the direction transverse to the propagation. Such surface waves are guided transmission line modes. For further explanation, reference is made to Friedman, B., *Principles and Techniques of Applied Mathematics*, Wiley, 1956, pp. pp. 214, 283-286, 290, 298-300.

[0026] In free space, antennas excite the continuum eigenvalues of the wave equation, which is a radiation field, where the outwardly propagating RF energy with E_z and H_ϕ in-phase is lost forever. On the other hand, waveguide probes excite discrete eigenvalues, which results in transmission line propagation. See Collin, R. E., *Field Theory of Guided Waves*, McGraw-Hill, 1960, pp. 453, 474-477. While such theoretical analyses have held out the hypothetical possibility of launching open surface guided waves over planar or spherical surfaces of lossy, homogeneous media, for more than a century no known structures in the engineering arts have existed for accomplishing this with any practical efficiency. Unfortunately, since it emerged in the early 1900's, the theoretical analysis set forth above has essentially remained a theory and there have been no known structures for practically accomplishing the launching of open surface guided waves over planar or spherical surfaces of lossy, homogeneous media.

[0027] According to the various embodiments of the present disclosure, various polyphase waveguide probes are described that are configured to excite radial surface currents having resultant fields that synthesize the form of surface-waveguide modes along the surface of a lossy conducting medium. Such guided electromagnetic fields are substantially mode-matched in magnitude and phase to a guided surface wave mode on the surface of the lossy conducting medium. Such a guided surface wave mode may also be termed a Zenneck surface wave mode. By virtue of the fact that the resultant fields excited by the polyphase waveguide probes described herein are substantially mode-matched to a Zenneck surface wave mode on the surface of the lossy conducting medium, a guided electromagnetic field in the form of a Zenneck surface wave is launched along the surface of the lossy conducting medium. According to one embodiment, the lossy conducting medium comprises a terrestrial medium such as the Earth.

[0028] Referring to FIG. 2, shown is a propagation interface that provides for an examination of the boundary value

solution to Maxwell's equations derived in 1907 by Jonathan Zenneck as set forth in his paper Zenneck, J., "On the Propagation of Plane Electromagnetic Waves Along a Flat Conducting Surface and their Relation to Wireless Telegraphy," Annalen der Physik, Serial 4, Vol. 23, Sep. 20, 1907, pp. 846-866. FIG. 2 depicts cylindrical coordinates for radially propagating waves along the interface between a lossy conducting medium specified as Region 1 and an insulator specified as Region 2. Region 1 may comprise, for example, any lossy conducting medium. In one example, such a lossy conducting medium may comprise a terrestrial medium such as the Earth or other medium. Region 2 is a second medium that shares a boundary interface with Region 1 and has different constitutive parameters relative to Region 1. Region 2 may comprise, for example, any insulator such as the atmosphere or other medium. The reflection coefficient for such a boundary interface goes to zero only for incidence at a complex Brewster angle. See Stratton, J. A., *Electromagnetic Theory*, McGraw-Hill, 1941, p. 516.

[0029] According to various embodiments, the present disclosure sets forth various polyphase waveguide probes that generate electromagnetic fields that are substantially mode-matched to a Zenneck surface wave mode on the surface of the lossy conducting medium comprising Region 1. According to various embodiments, such electromagnetic fields substantially synthesize a wave front incident at a complex Brewster angle of the lossy conducting medium that results in zero reflection.

[0030] To explain further, in Region 2, where $e^{j\omega t}$ field variation is assumed and where $\rho \neq 0$ and $z \geq 0$ (z is a vertical coordinate normal to the surface of Region 1, ρ is the radial dimension in cylindrical coordinates), Zenneck's closed-form exact solution of Maxwell's equations satisfying the boundary conditions along the interface are expressed by the following electric field and magnetic field components:

$$H_{2\phi} = A e^{-u_2 z} H_1^{(2)}(-j\gamma\rho), \tag{1}$$

$$E_{2\rho} = A\left(\frac{u_2}{j\omega\varepsilon_o}\right) e^{-u_2 z} H_1^{(2)}(-j\gamma\rho), \tag{2}$$

and

$$E_{2z} = A\left(\frac{-\gamma}{\omega\varepsilon_o}\right) e^{-u_2 z} H_0^{(2)}(-j\gamma\rho). \tag{3}$$

[0031] In Region 1, where $e^{j\omega t}$ field variation is assumed and where $\rho \neq 0$ and $z \leq 0$, Zenneck's closed-form exact solution of Maxwell's equations satisfying the boundary conditions along the interface are expressed by the following electric field and magnetic field components:

$$H_{1\phi} = A e^{u_1 z} H_1^{(2)}(-j\gamma\rho), \tag{4}$$

$$E_{1\rho} = A\left(\frac{-u_1}{\sigma_1 + j\omega\varepsilon_1}\right) e^{u_1 z} H_1^{(2)}(-j\gamma\rho), \tag{5}$$

and

$$E_{1z} = A\left(-\frac{j\gamma}{\sigma_1 + j\omega\varepsilon_1}\right) e^{u_1 z} H_0^{(2)}(-j\gamma\rho). \tag{6}$$

In these expressions, $H_n^{(2)}(-j\gamma\rho)$ is a complex argument Hankel function of the second kind and order n, u_1 is the propa-

gation constant in the positive vertical direction in Region 1, u_2 is the propagation constant in the vertical direction in Region 2, σ_1 is the conductivity of Region 1, ω is equal to $2\pi f$, where f is a frequency of excitation, ε_o is the permittivity of free space, ε_1 is the permittivity of Region 1, A is a source constant imposed by the source, z is a vertical coordinate normal to the surface of Region 1, γ is a surface wave radial propagation constant, and ρ is the radial coordinate.

[0032] The propagation constants in the $\pm z$ directions are determined by separating the wave equation above and below the interface between Regions 1 and 2, and imposing the boundary conditions. This exercise gives, in Region 2,

$$u_2 = \frac{-jk_o}{\sqrt{1 + (\varepsilon_r - jx)}}, \tag{7}$$

and gives, in Region 1,

$$u_1 = -u_2(\varepsilon_r - jx). \tag{8}$$

The radial propagation constant γ is given by

$$\gamma = j\sqrt{k_o^2 + u_2^2}, \tag{9}$$

which is a complex expression. In all of the above Equations,

$$x = \frac{\sigma_1}{\omega\varepsilon_0}, \text{ and} \tag{10}$$

$$k_0 = \omega\sqrt{\mu_o\varepsilon_o}, \tag{11}$$

where μ_o comprises the permeability of free space, ε_r comprises relative permittivity of Region 1. Thus, the surface wave generated propagates parallel to the interface and exponentially decays vertical to it. This is known as evanescence.

[0033] Thus, Equations (1)-(3) may be considered to be a cylindrically-symmetric, radially-propagating waveguide mode. See Barlow, H. M., and Brown, J., *Radio Surface Waves*, Oxford University Press, 1962, pp. 10-12, 29-33. The present disclosure details structures that excite this "open boundary" waveguide mode. Specifically, according to various embodiments, a polyphase waveguide probe is provided with charge terminals of appropriate size that are positioned relative to each other and are fed with voltages and/or currents so as to excite the relative phasing of the fields of the surface waveguide mode that is to be launched along the boundary interface between Region 2 and Region 1.

[0034] To continue further, the Leontovich impedance boundary condition between Region 1 and Region 2 is stated as

$$\hat{n} \times \vec{H}_2(\rho, \phi, 0) = \vec{J}_S, \tag{12}$$

where $\hat{n}$ is a unit normal in the positive vertical (+z) direction and $\vec{H}_2$ is the magnetic field strength in Region 2 expressed by Equation (1) above. Equation (12) implies that the fields specified in Equations (1)-(3) may be obtained by driving a radial surface current density along the boundary interface, such radial surface current density being specified by

$$J_\rho(\rho') = -A H_1^{(2)}(-j\gamma\rho') \tag{13}$$

where A is a constant yet to be determined. Further, it should be noted that close-in to the polyphase waveguide probe (for $\rho \ll \lambda$), Equation (13) above has the behavior

$$J_{close}(\rho') = \frac{-A(j2)}{\pi(-j\gamma\rho)} = -H_\phi = -\frac{I_o}{2\pi\rho'}. \tag{14}$$

[0035] One may wish to note the negative sign. This means that when source current flows vertically upward, the required "close-in" ground current flows radially inward. By field matching on H_ϕ "close-in" we find that

$$A = \frac{-I_o\gamma}{4} \tag{15}$$

in Equations (1)-(6) and (13). Therefore, Equation (13) may be restated as

$$J_\rho(\rho') = \frac{I_o\gamma}{4}H_1^{(2)}(-j\gamma\rho'). \tag{16}$$

[0036] With reference then to FIG. 3, shown is an example of a polyphase waveguide probe 200 that includes a charge terminal T_1 and a charge terminal T_2 that are arranged along a vertical axis z. The polyphase waveguide probe 200 is disposed above a lossy conducting medium 203 according to an embodiment of the present disclosure. The lossy conducting medium 203 makes up Region 1 (FIG. 2) according to one embodiment. In addition, a second medium 206 shares a boundary interface with the lossy conducting medium 203 and makes up Region 2 (FIG. 2). The polyphase waveguide probe 200 includes a probe coupling circuit 209 that couples an excitation source 213 to the charge terminals T_1 and T_2 as is discussed in greater detail with reference to later figures.

[0037] The charge terminals T_1 and T_2 are positioned over the lossy conducting medium 203. The charge terminal T_1 may be considered a capacitor, and the charge terminal T_2 may comprise a counterpoise or lower capacitor as is described herein. According to one embodiment, the charge terminal T_1 is positioned at height H_1, and the charge terminal T_2 is positioned directly below T_1 along the vertical axis z at height H_2, where H_2 is less than H_1. The height h of the transmission structure presented by the polyphase waveguide probe 200 is $h=H_1-H_2$. Given the foregoing discussion, one can determine asymptotes of the radial Zenneck surface current on the surface of the lossy conducting medium $J_\rho(\rho)$ to be $J_1(\rho)$ close-in and $J_2(\rho)$ far-out, where

[0038] Close-in ($\rho<\lambda/8$):

$$J_\rho(\rho) \sim J_1 = \frac{I_1 + I_2}{2\pi\rho} + \frac{E_\rho^{QS}(Q_1) + E_\rho^{QS}(Q_2)}{Z_\rho}, \tag{17}$$

and

[0039] Far-out ($\rho>>\lambda/8$):

$$J_\rho(\rho) \sim J_2 = \frac{j\gamma\omega Q_1}{4} \times \sqrt{\frac{2\gamma}{\pi}} \times \frac{e^{-(\alpha+j\beta)\rho}}{\sqrt{\rho}} \tag{18}$$

where I_1 is the conduction current feeding the charge Q_1 on the first charge terminal T_1, and I_2 is the conduction current

feeding the charge Q_2 on the second charge terminal T_2. The charge Q_1 on the upper charge terminal T_1 is determined by $Q_1=C_1V_1$, where C_1 is the isolated capacitance of the charge terminal T_1. Note that there is a third component to J_1 set forth above given by

$$\frac{(E_\rho^{Q1})}{Z_\rho},$$

which follows from the Leontovich boundary condition and is the radial current contribution in the lossy conducting medium 203 pumped by the quasi-static field of the elevated oscillating charge on the first charge terminal Q_1. The quantity

$$Z_\rho = \frac{j\omega\mu_o}{\gamma_e}$$

is the radial impedance of the lossy conducting medium, where $\gamma_e=(j\omega\mu_1\sigma_1-\omega^2\mu_1\in_1)^{1/2}$.

[0040] The asymptotes representing the radial current close-in and far-out as set forth by Equations (17) and (18) are complex quantities. According to various embodiments, a physical surface current, $J(r)$, is synthesized to match as close as possible the current asymptotes in magnitude and phase. That is to say close-in, $|J(r)|$ is to be tangent to $|J_1|$, and far-out $|J(r)|$ is to be tangent to $|J_2|$. Also, according to the various embodiments, the phase of $J(r)$ should transition from the phase of J_1 close-in to the phase of J_2 far-out.

[0041] According to one embodiment, if any of the various embodiments of a polyphase waveguide probe described herein are adjusted properly, this configuration will give at least an approximate magnitude and phase match to the Zenneck mode and launch Zenneck surface waves. It should be noted that the phase far-out, ϕ_2, is proportional to the propagation phase corresponding to $e^{-j\beta\rho}$ plus a fixed "phase boost" due to the phase of $\sqrt{\gamma}$ which is $arg(\sqrt{\gamma})$,

$$j\Phi_2(\rho)=-j\beta\rho+arg(\sqrt{\gamma}) \tag{19}$$

where γ is expressed in Equation (9) above, and depending on the values for $\in_r$ and σ at the site of transmission on the lossy conducting medium and the operating frequency f, $arg(\sqrt{\gamma})$, which has two complex roots, is typically on the order of approximately 45° or 225°. Stated another way, in order to match the Zenneck surface wave mode at the site of transmission to launch a Zenneck surface wave, the phase of the surface current $|J_2|$ far-out should differ from the phase of the surface current $|J_1|$ close-in by the propagation phase corresponding to $e^{-j\beta(\rho_2-\rho_1)}$ plus a constant of approximately 45 degrees or 225 degrees. This is because there are two roots for $\sqrt{\gamma}$, one near $\pi/4$ and one near $5\pi/4$. The properly adjusted synthetic radial surface current is

$$J_\rho(\rho, \phi, 0) = \frac{I_o\gamma}{4}H_1^{(2)}(-j\gamma\rho). \tag{20}$$

[0042] By Maxwell's equations, such a $J(\rho)$ surface current automatically creates fields that conform to

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$$H_\phi = \frac{-\gamma I_o}{4} e^{-u_2 z} H_1^{(2)}(-j\gamma\rho),$$ (21)

$$E_\rho = \frac{-\gamma I_o}{4}\left(\frac{u_2}{j\omega\varepsilon_o}\right)e^{-u_2 z} H_1^{(2)}(-j\gamma\rho),\text{ and}$$ (22)

$$E_z = \frac{-\gamma I_o}{4}\left(\frac{-\gamma}{\omega\varepsilon_o}\right)e^{-u_2 z} H_0^{(2)}(-j\gamma\rho).$$ (23)

[0043] Thus, the difference in phase between the surface current $|J_2|$ far-out and the surface current $|J_1|$ close-in for the Zenneck surface wave mode that is to be matched is due to the inherent characteristics of the Hankel functions in Equations (20)-(23) set forth above. It is of significance to recognize that the fields expressed by Equations (1)-(6) and (20) have the nature of a transmission line mode bound to a lossy interface, not radiation fields such as are associated with groundwave propagation. See Barlow, H. M. and Brown, J., *Radio Surface Waves*, Oxford University Press, 1962, pp. 1-5. These fields automatically satisfy the complex Brewster angle requirement for zero reflection, which means that radiation is negligible, while surface guided wave propagation is dramatically enhanced, as is verified and supported in the experimental results provided below.

[0044] At this point, a review of the nature of the Hankel functions used in Equations (20)-(23) is provided with emphasis on a special property of these solutions of the wave equation. One might observe that the Hankel functions of the first and second kind and order n are defined as complex combinations of the standard Bessel functions of the first and second kinds

$$H_n^{(1)}(x)=J_n(x)+jN_n(x)\text{ and}$$ (24)

$$H_n^{(2)}(x)=J_n(x)-jN_n(x).$$ (25)

[0045] These functions represent cylindrical waves propagating radially inward (superscript (1)) and outward (superscript (2)), respectively. The definition is analogous to the relationship $e^{\pm jx}=\cos x\pm j\sin x$. See, for example, Harrington, R. F., *Time-Harmonic Fields*, McGraw-Hill, 1961, pp. 460-463.

[0046] That $H_n^{(2)}(k_\rho\rho)$ is an outgoing wave is easily recognized from its large argument asymptotic behavior that is obtained directly from the series definitions of $J_n(x)$ and $N_n(x)$,

$$H_n^{(2)}(x)\xrightarrow[x\to\infty]{}\sqrt{\frac{2j}{\pi x}}\,j^n e^{-jx}$$ (26)

which, when multiplied by $e^{j\omega t}$, is an outward propagating cylindrical wave of the form $e^{j(\omega t-k\rho)}$ with a $1/\sqrt{\rho}$ spatial variation. The phase of the exponential component is $\psi=(\omega t-k\rho)$. It is also evident that

$$H_n^{(2)}(x)\xrightarrow[x\to\infty]{}j^n H_0^{(2)}(x),$$ (27)

and, a further useful property of Hankel functions is expressed by

$$\frac{\partial H_0^{(2)}(x)}{\partial x}=-H_1^{(2)}(x),$$ (28)

which is described by Jahnke, E., and F. Emde, *Tables of Functions*, Dover, 1945, p. 145.

[0047] In addition, the small argument and large argument asymptotes of the outward propagating Hankel function are as follows:

$$H_1^{(2)}(x)\xrightarrow[x\to 0]{}\frac{j2}{\pi x}$$ (29)

$$H_1^{(2)}(x)\xrightarrow[x\to\infty]{}j\sqrt{\frac{2j}{\pi x}}\,e^{-jx}=\sqrt{\frac{2}{\pi x}}\,e^{-j\left(x-\frac{\pi}{2}-\frac{\pi}{4}\right)}.$$ (30)

[0048] Note that these asymptotic expressions are complex quantities. Also, unlike ordinary sinusoidal functions, the behavior of complex Hankel functions differs in-close and far-out from the origin. When x is a real quantity, Equations (29) and (30) differ in phase by $\sqrt{j}$, which corresponds to an extra phase advance or "phase boost" of 45° or, equivalently $\lambda/8$.

[0049] With reference to FIG. 4, to further illustrate the phase transition between J_1 (FIG. 3) and J_2 (FIG. 3) shown is an illustration of the phases of the surface currents J_1 close-in and J_2 far-out relative to a position of a polyphase waveguide probe 200 (FIG. 3). As shown in FIG. 4, there are three different observation points P_0, P_1, and P_2. A transition region is located between the observation point P_1 and observation point P_2. The observation point P_0 is located at the position of the polyphase waveguide probe 200. The observation point P_1 is positioned "close-in" at a distance R_1 from the observation point P_0 that places the observation point P_1 between the transition region 216 and the observation point P_0. The observation point P_2 is positioned "far-out" at a distance R_2 from the observation point P_0 beyond the transition region 216 as shown.

[0050] At observation point P_0, the magnitude and phase of the radial current J is expressed as $|J_{P_0}|\angle\phi_0$. At observation point P_1, the magnitude and phase of the radial current J is expressed as $|J_{P_1}|\angle\phi_0-\beta R_1$, where the phase shift of βR_1 is attributable to the distance R_1 between the observation points P_0 and P_1. At observation point P_2, the magnitude and phase of the radial current J is expressed as $|J_{P_2}|\angle\phi_0-\beta R_1+\phi_\Delta$ where the phase shift of $\beta R_1+\phi_\Delta$ is attributable to the distance R_2 between the observation points P_0 and P_2 AND an additional phase shift that occurs in the transition region 216. The additional phase shift ϕ_Δ occurs as a property of the Hankel function as mentioned above.

[0051] The foregoing reflects the fact that the polyphase waveguide probe 200 generates the surface current J_1 close-in and then transitions to the J_2 current far-out. In the transition region 216, the phase of the Zenneck surface-waveguide mode transitions by approximately 45 degrees or $\frac{1}{8}\lambda$. This transition or phase shift may be considered a "phase boost" as the phase of the Zenneck surface-waveguide mode appears to advance by 45 degrees in the transition region 216. The transition region 216 appears to occur somewhere less than $\frac{1}{10}$ of a wavelength of the operating frequency.

[0052] Referring back to FIG. 3, according to one embodiment, a polyphase waveguide probe may be created that will

launch the appropriate radial surface current distribution. According to one embodiment, a Zenneck waveguide mode is created in a radial direction. If the J(r) given by Equation (20) can be created, it will automatically launch Zenneck surface waves.

[0053] In addition, further discussion is provided regarding the charge images Q_1' and Q_2' of the charges Q_1 and Q_2 on the charge terminals T_1 and T_2 of one example polyphase waveguide probe shown in FIG. 3. Analysis with respect to the lossy conducting medium assumes the presence of induced effective image charges Q_1' and Q_2' beneath the polyphase waveguide probes coinciding with the charges Q_1 and Q_2 on the charge reservoirs T_1 and T_2 as described herein. Such image charges Q_1' and Q_2' must also be considered in the analysis. These image charges Q_1' and Q_2' are not merely 180° out of phase with the primary source charges Q_1 and Q_2 on the charge reservoirs T_1 and T_2, as they would be in the case of a perfect conductor. A lossy conducting medium such as, for example, a terrestrial medium presents phase shifted images. That is to say, the image charges Q_1' and Q_2' are at complex depths. For a discussion of complex images, reference is made to Wait, J. R., "Complex Image Theory—Revisited," *IEEE Antennas and Propagation Magazine*, Vol. 33, No. 4, August 1991, pp. 27-29, which is incorporated herein by reference in its entirety.

[0054] Instead of the image charges Q_1' and Q_2' being at a depth that is equal to the height of the charges Q_1 and Q_2 (i.e. $z_n'=-h_n$), a conducting mirror 215 is placed at depth $z=-d/2$ and the image itself appears at a "complex distance" (i.e., the "distance" has both magnitude and phase), given by $z_n'=-D_n=-(d+h_n)\neq-h_n$, where n=1, 2, and for vertically polarized sources,

$$d = \frac{2\sqrt{\gamma_e^2 + k_o^2}}{\gamma_e^2} \approx \frac{2}{\gamma_e} = d_r + jd_i = |d|\angle\zeta, \tag{31}$$

where

$$\gamma_e^2 = j\omega\mu_1\sigma_1 - \omega^2\mu_1\varepsilon_1, \text{ and} \tag{32}$$

$$k_o = \omega\sqrt{\mu_o\varepsilon_o}. \tag{33}$$

[0055] The complex spacing of image charges Q_1' and Q_2', in turn, implies that the external fields will experience extra phase shifts not encountered when the interface is either a lossless dielectric or a perfect conductor. The essence of the lossy dielectric image-theory technique is to replace the finitely conducting Earth (or lossy dielectric) by a perfect conductor located at a complex depth, $z=-d/2$. Next, a source image is then located at a complex depth $D_n=d/2+d/2+h_n=d+h_n$, where n=1, 2. Thereafter, one can calculate the fields above ground ($z\geq0$) using a superposition of the physical charge (at $z=+h$) plus its image (at $z'=-D$). The charge images Q_1' and Q_2' at complex depths actually assist in obtaining the desired current phases specified in Equations (20) and (21) above.

[0056] From Equations (2) and (3) above, it is noted that the ratio of E_{2z} to $E_{2\rho}$ in Region 2 is given by

$$\frac{E_{2z}}{E_{2\rho}} = \frac{A\left(\frac{-\gamma}{\omega\varepsilon_o}\right)e^{-u_{2}z}H_0^{(2)}(-j\gamma\rho)}{A\left(\frac{u_2}{j\omega\varepsilon_o}\right)e^{-u_{2}z}H_1^{(2)}(-j\gamma\rho)} = \left(\frac{-j\gamma}{u_2}\right)\frac{H_0^{(2)}(-j\gamma\rho)}{H_1^{(2)}(-j\gamma\rho)}. \tag{34}$$

Also, it should be noted that asymptotically,

$$H_n^{(2)}(x)\xrightarrow{x\to\infty} j^n H_0^{(2)}(x). \tag{35}$$

Consequently, it follows directly from Equations (2) and (3) that

$$\frac{E_{2z}}{E_{2\rho}} = \sqrt{\varepsilon_r - jx} = n = \tan\psi_{i,B}, \tag{36}$$

where $\psi_{i,B}$ is the complex Brewster angle. By adjusting source distributions and synthesizing complex Brewster angle illumination at the surface of a lossy conducting medium 203, Zenneck surface waves may be excited.

[0057] With reference to FIG. 5, shown is an incident field E polarized parallel to a plane of incidence. The electric field vector E is to be synthesized as an incoming non-uniform plane wave, polarized parallel to the plane of incidence. The electric field vector E may be created from independent horizontal and vertical components as:

$$\vec{E}(\theta_o)=E_\rho\hat{\rho}+E_z\hat{z}. \tag{37}$$

Geometrically, the illustration in FIG. 5 suggests:

$$E_\rho(\rho,z)=E(\rho,z)\cos\psi_o, \text{ and} \tag{38a}$$

$$E_z(\rho, z) = E(\rho, z)\cos\left(\frac{\pi}{2} - \psi_o\right) = E(\rho, z)\sin\psi_o, \tag{38b}$$

which means that the field ratio is

$$\frac{E_z}{E_\rho} = \tan\psi_o. \tag{39}$$

However, recall that from Equation (36),

$$\tan\theta_{i,B}=\sqrt{\varepsilon_r-jx} \tag{40}$$

so that, for a Zenneck surface wave, we desire $\psi_o=\theta_{i,B}$, which results in

$$\frac{E_z}{E_\rho} = \tan\psi_o = \sqrt{\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_o}}. \tag{41}$$

[0058] The Equations mean that if one controls the magnitude of the complex field ratio and the relative phase between the incident vertical and horizontal components E_z and E_ρ in a plane parallel to the plane of incidence, then the synthesized E-field vector will effectively be made to be incident at a complex Brewster angle. Such a circumstance will syntheti-

cally excite a Zenneck surface wave over the interface between Region 1 and Region 2.

[0059] With reference to FIG. 6, shown is another view of the polyphase waveguide probe 200 disposed above a lossy conducting medium 203 according to an embodiment of the present disclosure. The lossy conducting medium 203 makes up Region 1 (FIG. 2) according to one embodiment. In addition, a second medium 206 shares a boundary interface with the lossy conducting medium 203 and makes up Region 2 (FIG. 2).

[0060] According to one embodiment, the lossy conducting medium 203 comprises a terrestrial medium such as the planet Earth. To this end, such a terrestrial medium comprises all structures or formations included thereon whether natural or man-made. For example, such a terrestrial medium may comprise natural elements such as rock, soil, sand, fresh water, sea water, trees, vegetation, and all other natural elements that make up our planet. In addition, such a terrestrial medium may comprise man-made elements such as concrete, asphalt, building materials, and other man-made materials. In other embodiments, the lossy conducting medium 203 may comprise some medium other than the Earth, whether naturally occurring or man-made. In other embodiments, the lossy conducting medium 203 may comprise other media such as man-made surfaces and structures such as automobiles, aircraft, man-made materials (such as plywood, plastic sheeting, or other materials) or other media.

[0061] In the case that the lossy conducting medium 203 comprises a terrestrial medium or Earth, the second medium 206 may comprise the atmosphere above the ground. As such, the atmosphere may be termed an "atmospheric medium" that comprises air and other elements that make up the atmosphere of the Earth. In addition, it is possible that the second medium 206 may comprise other media relative to the lossy conducting medium 203.

[0062] The polyphase waveguide probe 200 comprises a pair of charge terminals T_1 and T_2. Although two charge terminals T_1 and T_2 are shown, it is understood that there may be more than two charge terminals T_1 and T_2. According to one embodiment, the charge terminals T_1 and T_2 are positioned above the lossy conducting medium 203 along a vertical axis z that is normal to a plane presented by the lossy conducting medium 203. In this respect, the charge terminal T_1 is placed directly above the charge terminal T_2 although it is possible that some other arrangement of two or more charge terminals T_N may be used. According to various embodiments, charges Q_1 and Q_2 may be imposed on the respective charge terminals T_1 and T_2.

[0063] The charge terminals T_1 and/or T_2 may comprise any conductive mass that can hold an electrical charge. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. The charge terminals T_1 and/or T_2 may comprise any shape such as a sphere, a disk, a cylinder, a cone, a torus, a randomized shape, or any other shape. Also note that the charge terminals T_1 and T_2 need not be identical, but each can have a separate size and shape, and be comprises of different conducting materials. According to one embodiment, the shape of the charge terminal T_1 is specified to hold as much charge as practically possible. Ultimately, the field strength of a Zenneck surface wave launched by a polyphase waveguide probe 200 is directly proportional to the quantity of charge on the terminal T_1.

[0064] If the charge terminals T_1 and/or T_2 are spheres or disks, the respective self-capacitance C_1 and C_2 can be calcu-lated. For example, the self-capacitance of an isolated conductive sphere is $C=4\pi\in_o r$, where r comprises the radius of the sphere in meters. The self-capacitance of an isolated disk is $C=8\in_o r$, where r comprises the radius of the disk in meters.

[0065] Thus, the charge Q_1 stored on the charge terminal T_1 may be calculated as $Q_1=C_1 V$, given the self-capacitance C_1 of the charge reservoir T_1 and voltage V that is applied to the charge terminal T_1.

[0066] With further reference to FIG. 6, according to one embodiment, the polyphase waveguide probe 200 comprises a probe coupling circuit 209 that is coupled to the charge terminals T_1 and T_2. The probe coupling circuit 209 facilitates coupling the excitation source 213 to the charge terminals T_1 and T_2, and facilitates generating respective voltage magnitudes and phases on the charge terminals T_1 and T_2 for a given frequency of operation. If more than two charge terminals T_N are employed, then the probe coupling circuit 209 would be configured to facilitate the generation of various voltage magnitudes and phases on the respective charge terminals T_N relative to each other. In the embodiment of the polyphase waveguide probe 200, the probe coupling circuit 209 comprises various circuit configurations as will be described.

[0067] In one embodiment, the probe coupling circuit 209 is specified so as to make the polyphase waveguide probe 200 electrically half-wave resonant. This imposes a voltage +V on a first one of the terminals T_1 or T_2, and a −V on the second one of the charge terminals T_1 or T_2 at any given time. In such case, the voltages on the respective charge terminals T_1 and T_2 are 180 degrees out of phase as can be appreciated. In the case that the voltages on the respective charge terminals T_1 and T_2 are 180 degrees out of phase, the largest voltage magnitude differential is experienced on the charge terminals T_1 and T_2. Alternatively, the probe coupling circuit 209 may be configured so that the phase differential between the charge terminals T_1 and T_2 is other than 180 degrees. To this end, the probe coupling circuit 209 may be adjusted to alter the voltage magnitudes and phases during adjustment of the polyphase waveguide probe 200.

[0068] By virtue of the placement of the charge terminal T_1 directly above the charge terminal T_2, a mutual capacitance C_M is created between the charge terminals T_1 and T_2. Also, the charge terminal T_1 has self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2 as mentioned above. There may also be a bound capacitance between the charge terminal T_1 and the lossy conducting medium 203, and a bound capacitance between the charge terminal T_2 and the lossy conducting medium 203, depending on the respective heights of the charge terminals T_1 and T_2. The mutual capacitance C_M depends on the distance between the charge terminals T_1 and T_2.

[0069] Ultimately, the field strength generated by the polyphase waveguide probe 200 will be directly proportional to the magnitude of the charge Q_1 that is imposed on the upper terminal T_1. The charge Q_1 is, in turn, proportional to the self-capacitance C_1 associated with the charge terminal T_1 since $Q_1=C_1 V$, where V is the voltage imposed on the charge terminal T_1.

[0070] According to one embodiment, an excitation source 213 is coupled to the probe coupling circuit 209 in order to apply a signal to the polyphase waveguide probe 200. The excitation source 213 may be any suitable electrical source such as a voltage or current source capable of generating the voltage or current at the operating frequency that is applied to the polyphase waveguide probe 200. To this end, the excita-

tion source **213** may comprise, for example, a generator, a function generator, transmitter, or other electrical source.

[0071] In one embodiment, the excitation source **213** may be coupled to the polyphase waveguide probe **200** by way of magnetic coupling, capacitive coupling, or conductive (direct tap) coupling as will be described. In some embodiments, the probe coupling circuit **209** may be coupled to the lossy conducting medium **203**. Also, in various embodiments, the excitation source **213** maybe coupled to the lossy conducting medium **203** as will be described.

[0072] In addition, it should be noted that, according to one embodiment, the polyphase waveguide probe **200** described herein has the property that its radiation resistance R_r is very small or even negligible. One should recall that radiation resistance R_r is the equivalent resistance that would dissipate the same amount of power that is ultimately radiated from an antenna. According to the various embodiments, the polyphase waveguide probe **200** launches a Zenneck surface wave that is a guided electromagnetic wave. According to the various embodiments, the polyphase waveguide probes described herein have little radiation resistance R_r because the height of such polyphase waveguide probes is usually small relative to their operating wavelengths. Stated another way, according to one embodiment, the polyphase waveguide probes described herein are "electrically small." As contemplated herein, the phrase "electrically small" is defined as a structure such as the various embodiments of polyphase waveguide probes described herein that can be physically bounded by a sphere having a radius equal to $\lambda/2\pi$, where λ is the free-space wavelength. See Fujimoto, K., A. Henderson, K. Hirasawa, and J. R. James, Small Antennas, *Wiley*, 1987, p. 4.

[0073] To discuss further, the radiation resistance R_r for a short monopole antenna is expressed by

$$R_r = 160 \, \pi^2 \left(\frac{h}{\lambda}\right)^2 \tag{42}$$

where the short monopole antenna has a height h with a uniform current distribution, and where λ is the wavelength at the frequency of operation. See Stutzman, W. L. et al., "*Antenna Theory and Design*," Wiley & Sons, 1981, p. 93.

[0074] Given that the value of the radiation resistance R_r is determined as a function of

$$\left(\frac{h}{\lambda}\right)^2,$$

it follows that if the height h of the structure is small relative to the wavelength of the operating signal at the operating frequency, then the radiation resistance R_r will also be small. As one example, if the height h of the transmission structure is 10% of the wavelength of the operating signal at the operating frequency, then the resulting value of

$$\left(\frac{h}{\lambda}\right)^2$$

would be $(0.1)^2=0.01$. It would follow that the radiation resistance R_r is correspondingly small.

[0075] Thus, according to various embodiments, if the effective height h of the transmission structure is less than or equal to

$$\frac{\lambda}{2\pi},$$

where λ is the wavelength at the operating frequency, then the radiation resistance R_r will be relatively small. For the various embodiments of polyphase waveguide probes **200** described below, the height h of the transmission structure may be calculated as $h=H_1-H_2$, where H_1 is the height of the charge terminal T_1, and H_2 is the height of the charge terminal T_2. It should be appreciated that the height h of the transmission structure for each embodiment of the polyphase waveguide probes **200** described herein can be determined in a similar manner.

[0076] While

$$\frac{\lambda}{2\pi}$$

is provided as one benchmark, it is understood that the ratio of the height h of the transmission structure over the wavelength of the operating signal at the operating frequency can be any value. However, it is understood that, at a given frequency of operation, as the height of a given transmission structure increases, the radiation resistance R_r will increase accordingly.

[0077] Depending on the actual values for the height h and the wavelength of the operating signal at the operating frequency, it is possible that the radiation resistance R_r may be of a value such that some amount of radiation may occur along with the launching of a Zenneck surface wave. To this end, the polyphase waveguide probe **200** can be constructed to have a short height h relative to the wavelength at the frequency of operation so as to ensure that little or substantially zero energy is lost in the form of radiation.

[0078] In addition, the placement of the charge reservoirs T_1 and T_2 along the vertical axis z provides for symmetry in the Zenneck surface wave that is launched by the polyphase waveguide probe **200** as described by the Hankel functions in Equations (20)-(23) set forth above. Although the polyphase waveguide probe **200** is shown with two charge reservoirs T_1 and T_2 along the vertical axis z that is normal to a plane making up the surface of the lossy conducting medium **203**, it is understood that other configurations may be employed that will also provide for the desired symmetry. For example, additional charge reservoirs T_N may be positioned along the vertical axis z, or some other arrangement may be employed. In some embodiments, symmetry of transmission may not be desired. In such case, the charge reservoirs T_N may be arranged in a configuration other than along a vertical axis z to provide for an alternative transmission distribution pattern.

[0079] When properly adjusted to operate at a predefined operating frequency, the polyphase waveguide probe **200** generates a Zenneck surface wave along the surface of the lossy conducting medium **203**. To this end, an excitation source **213** may be employed to generate electrical energy at a predefined frequency that is applied to the polyphase waveguide probe **200** to excite the structure. The energy from the excitation source **213** is transmitted in the form of a

Zenneck surface wave by the polyphase waveguide probe **200** to one or more receivers that are also coupled to the lossy conducting medium **203** or that are located within an effective transmission range of the polyphase waveguide probe **200**. The energy is thus conveyed in the form of a Zenneck surface wave which is a surface-waveguide mode or a guided electromagnetic field. In the context of modern power grids using high voltage lines, a Zenneck surface wave comprises a transmission line mode.

[0080] Thus, the Zenneck surface wave generated by the polyphase waveguide probe **200** is not a radiated wave, but a guided wave in the sense that these terms are described above. The Zenneck surface wave is launched by virtue of the fact that the polyphase waveguide probe **200** creates electromagnetic fields that are substantially mode-matched to a Zenneck surface wave mode on the surface of the lossy conducting medium **203**. When the electromagnetic fields generated by the polyphase waveguide probe **200** are substantially mode-matched as such, the electromagnetic fields substantially synthesize a wave front incident at a complex Brewster angle of the lossy conducting medium **203** that results in little or no reflection. Note that if the polyphase waveguide probe **200** is not substantially mode-matched to the Zenneck surface wave mode, then a Zenneck surface wave will not be launched since the complex Brewster angle of the lossy conducting medium **203** would not have been attained.

[0081] In the case that the lossy conducting medium **203** comprises a terrestrial medium such as the Earth, the Zenneck surface wave mode will depend upon the dielectric permittivity $\in_r$ and conductivity a of the site at which the polyphase waveguide probe **200** is located as indicated above in Equations (1)-(11). Thus, the phase of the Hankel functions in Equations (20)-(23) above depends on these constitutive parameters at the launch site and on the frequency of operation.

[0082] In order to excite the fields associated with the Zenneck surface wave mode, according to one embodiment, the polyphase waveguide probe **200** substantially synthesizes the radial surface current density on the lossy conducting medium of the Zenneck surface wave mode as is expressed by Equation (20) set forth above. When this occurs, the electromagnetic fields are then substantially or approximately mode-matched to a Zenneck surface wave mode on the surface of the lossy conducting medium **203**. To this end, the match should be as close as is practicable. According to one embodiment, this Zenneck surface wave mode to which the electromagnetic fields are substantially matched is expressed in Equations (21)-(23) set forth above.

[0083] In order to synthesize the radial surface current density in the lossy conducting medium of the Zenneck surface wave mode, the electrical characteristics of the polyphase waveguide probe **200** should be adjusted to impose appropriate voltage magnitudes and phases on the charge terminals T_1 and T_2 for a given frequency of operation and given the electrical properties of the site of transmission. If more than two charge terminals T_N are employed, then appropriate voltage magnitudes and phases would need to be imposed on the respective charge terminals T_N, where N may even be a very large number effectively comprising a continuum of charge terminals.

[0084] In order to obtain the appropriate voltage magnitudes and phases for a given design of a polyphase waveguide probe **200** at a given location, an iterative approach may be used. Specifically, analysis may be performed of a given

excitation and configuration of a polyphase waveguide probe **200** taking into account the feed currents to the terminals T_1 and T_2, the charges on the charge terminals T_1 and T_2, and their images in the lossy conducting medium **203** in order to determine the radial surface current density generated. This process may be performed iteratively until an optimal configuration and excitation for a given polyphase waveguide probe **200** is determined based on desired parameters. To aid in determining whether a given polyphase waveguide probe **200** is operating at an optimal level, a guided field strength curve **103** (FIG. 1) may be generated using Equations (1)-(11) above based on values for the conductivity of Region 1 (σ_1) and the permittivity of Region 1 ($\in_1$) at the location of the polyphase waveguide probe **200**. Such a guided field strength curve **103** will provide a benchmark for operation such that measured field strengths can be compared with the magnitudes indicated by the guided field strength curve **103** to determine if optimal transmission has been achieved.

[0085] In order to arrive at an optimized polyphase waveguide probe **200**, various parameters associated with the polyphase waveguide probe **200** may be adjusted. Stated another way, the various parameters associated with the polyphase waveguide probe **200** may be varied to adjust the polyphase waveguide probe **200** to a desired operating configuration.

[0086] One parameter that may be varied to adjust the polyphase waveguide probe **200** is the height of one or both of the charge terminals T_1 and/or T_2 relative to the surface of the lossy conducting medium **203**. In addition, the distance or spacing between the charge terminals T_1 and T_2 may also be adjusted. In doing so, one may minimize or otherwise alter the mutual capacitance C_M or any bound capacitances between the charge terminals T_1 and T_2 and the lossy conducting medium **203** as can be appreciated.

[0087] Alternatively, another parameter that can be adjusted is the size of the respective charge terminals T_1 and/or T_2. By changing the size of the charge terminals T_1 and/or T_2, one will alter the respective self-capacitances C_1 and/or C_2, and the mutual capacitance C_M as can be appreciated. Also, any bound capacitances that exist between the charge terminals T_1 and T_2 and the lossy conducting medium **203** will be altered. In doing so, the voltage magnitudes and phases on the charge terminals T_1 and T_2 are altered.

[0088] Still further, another parameter that can be adjusted is the probe coupling circuit **209** associated with the polyphase waveguide probe **200**. This may be accomplished by adjusting the size of the inductive and/or capacitive reactances that make up the probe coupling circuit **209**. For example, where such inductive reactances comprise coils, the number of turns on such coils may be adjusted. Ultimately, the adjustments to the probe coupling circuit **209** can be made to alter the electrical length of the probe coupling circuit **209**, thereby affecting the voltage magnitudes and phases on the charge terminals T_1 and T_2.

[0089] It is also the case that one can adjust the frequency of an excitation source **213** applied to the polyphase waveguide probe **200** to optimize the transmission of a Zenneck surface wave. However, if one wishes to transmit at a given frequency, other parameters would need to be adjusted to optimize transmission.

[0090] Note that the iterations of transmission performed by making the various adjustments may be implemented by using computer models or by adjusting physical structures as can be appreciated. In one approach, a field meter tuned to the

transmission frequency may be placed an appropriate distance from the polyphase waveguide probe **200** and adjustments may be made as set forth above until a maximum or any other desired field strength of a resulting Zenneck surface wave is detected. To this end, the field strength may be compared with a guided field strength curve **103** (FIG. 1) generated at the desired operating frequency and voltages on the terminals T_1 and T_2. According to one approach, the appropriate distance for placement of such a field meter may be specified as greater than the transition region **216** (FIG. 4) in the "far-out" region described above where the surface current J_2 dominates.

[0091] By making the above adjustments, one can create corresponding "close-in" surface current J_1 and "far-out" surface current J_2 that approximate the same currents J(r) of the Zenneck surface wave mode specified in Equations (17) and (18) set forth above. In doing so, the resulting electromagnetic fields would be substantially or approximately mode-matched to a Zenneck surface wave mode on the surface of the lossy conducting medium **203**.

[0092] Referring next to FIGS. 7A through 7J, shown are additional examples of polyphase waveguide probes **200**, denoted herein as polyphase waveguide probes **200***a-j*, according to various embodiments of the present disclosure. The polyphase waveguide probes **200***a-j* each include a different probe coupling circuit **209**, denoted herein as probe coupling circuits **209***a-j*, according to various embodiments. While several examples of probe coupling circuits **209***a-j* are described, it is understood that these embodiments are merely examples and that there may be many other probe coupling circuits **209** not set forth herein that may be employed to provide for the desired voltage magnitudes and phases on the charge terminals T_1 and T_2 according to the principles set forth herein in order to facilitate the launching of Zenneck surface waves.

[0093] In addition, each of the probe coupling circuits **209***a-j* may employ, but are not limited to, inductive impedances comprising coils. Even though coils are used, it is understood that other circuit elements, both lumped and distributed, may be employed as reactances. Also, other circuit elements may be included in the probe coupling circuits **209***a-j* beyond those illustrated herein. In addition, it is noted that the various polyphase waveguide probes **200***a-j* with their respective probe coupling circuits **209***a-j* are merely described herein to provide examples. To this end, there may be many other polyphase waveguide probes **200** that employ various probe coupling circuits **209** and other circuitry that can be used to launch Zenneck surface waves according to the various principles set forth herein.

[0094] Referring now to FIG. 7A, shown is a first example of the polyphase waveguide probe **200** (FIG. 6), denoted herein as polyphase waveguide probe **200***a*, according to one embodiment. The polyphase waveguide probe **200***a* includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium **203**. The second medium **206** is above the lossy conducting medium **203**. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition,

bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium **203** depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium **203**.

[0095] The polyphase waveguide probe **200***a* includes a probe coupling circuit **209***a* that comprises an inductive impedance comprising a coil L_{1a} having a pair of leads that are coupled to respective ones of the charge terminals T_1 and T_2. In one embodiment, the coil L_{1a} is specified to have an electrical length that is one-half (½) of the wavelength at the operating frequency of the polyphase waveguide probe **200***a*.

[0096] While the electrical length of the coil L_{1a} is specified as approximately one-half (½) the wavelength at the operating frequency, it is understood that the coil L_{1a} may be specified with an electrical length at other values. According to one embodiment, the fact that the coil L_{1a} has an electrical length of approximately one-half the wavelength at the operating frequency provides for an advantage in that a maximum voltage differential is created on the charge terminals T_1 and T_2. Nonetheless, the length or diameter of the coil L_{1a} may be increased or decreased when adjusting the polyphase waveguide probe **200***a* to obtain optimal excitation of a Zenneck surface wave mode. Alternatively, it may be the case that the inductive impedance is specified to have an electrical length that is significantly less than or greater than ½ the wavelength at the operating frequency of the polyphase waveguide probe **200***a*.

[0097] According to one embodiment, the excitation source **213** is coupled to the probe coupling circuit **209** by way of magnetic coupling. Specifically, the excitation source **213** is coupled to a coil L_P that is inductively coupled to the coil L_{1a}. This may be done by link coupling, a tapped coil, a variable reactance, or other coupling approach as can be appreciated. To this end, the coil L_P acts as a primary, and the coil L_{1a} acts as a secondary as can be appreciated.

[0098] In order to adjust the polyphase waveguide probe **200***a* for the transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium **203** and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of the coil L_{1a} may be altered by adding or eliminating turns or by changing some other dimension of the coil L_{1a}.

[0099] Based on experimentation with the polyphase waveguide probe **200***a*, this appears to be the easiest of the polyphase waveguide probes **200***a-j* to adjust and to operate to achieve a desired efficiency.

[0100] Referring now to FIG. 7B, shown is an example of the polyphase waveguide probe **200** (FIG. 6), denoted herein as polyphase waveguide probe **200***b*, according to one embodiment. The polyphase waveguide probe **200***b* includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium **203**. The second medium **206** is above the lossy conducting medium **203**. The charge terminals T_1 and T_2 are positioned along a vertical axis z to provide for cylindrical symmetry in the resulting Zenneck surface wave as was described above. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on

the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium 203.

[0101] The polyphase waveguide probe 200b also includes a probe coupling circuit 209b comprising a first coil L_{1b} and a second coil L_{2b}. The first coil L_{1b} is coupled to each of the charge terminals T_1 and T_2 as shown. The second coil L_{2b} is coupled to the charge terminal T_2 and to the lossy conducting medium 203.

[0102] The excitation source 213 is magnetically coupled to the probe coupling circuit 209b in a manner similar as was mentioned with respect to the polyphase waveguide probe 200a (FIG. 7A) set forth above. To this end, the excitation source 213 is coupled to a coil L_P that acts as a primary and the coil L_{1b} acts as a secondary. Alternatively, the coil L_{2b} may act as a secondary as well.

[0103] In order to adjust the polyphase waveguide probe 200b for the transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of each of the coils L_{1b} and L_{2b} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1b} or L_{2b}.

[0104] Referring now to FIG. 7C, shown is another example of the polyphase waveguide probe 200 (FIG. 6), denoted herein as polyphase waveguide probe 200c, according to one embodiment. The polyphase waveguide probe 200c includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. The second medium 206 is above the lossy conducting medium 203. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium 203.

[0105] The polyphase waveguide probe 200c also includes a probe coupling circuit 209c comprising a coil L_{1c}. One end of the coil L_{1c} is coupled to the charge terminal T_1 as shown. The second end of the coil L_{1c} is coupled to the lossy conducting medium 203. A tap that is coupled to the charge terminal T_2 is positioned along the coil L_{1c}.

[0106] The excitation source 213 is magnetically coupled to the probe coupling circuit 209c in a manner similar as was mentioned with respect to the polyphase waveguide probe 200a (FIG. 7A) set forth above. To this end, the excitation source 213 is coupled to a coil L_P that acts as a primary and the coil L_{1c} acts as a secondary. The coil L_P can be positioned at any location along the coil L_{1c}.

[0107] In order to adjust the polyphase waveguide probe 200c for the excitation and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of the coil L_{1c} may be altered by adding or eliminating turns, or by changing some other dimension of the coil L_{1c}. In addition, the inductance presented by the portions of the coil L_{1c} above and below the tap may be adjusted by moving the position of the tap.

[0108] Referring now to FIG. 7D, shown is yet another example of the polyphase waveguide probe 200 (FIG. 6), denoted herein as polyphase waveguide probe 200d, according to one embodiment. The polyphase waveguide probe 200d includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. The second medium 206 is above the lossy conducting medium 203. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium 203.

[0109] The polyphase waveguide probe 200d also includes a probe coupling circuit 209d comprising a first coil L_{1d} and a second coil L_{2d}. A first lead of the first coil L_{1d} is coupled to the charge terminal T_1, and the second lead of the first coil L_{1d} is coupled to the lossy conducting medium 203. A first lead of the second coil L_{2d} is coupled to the charge terminal T_2, and the second lead of the second coil L_{2d} is coupled to the lossy conducting medium 203.

[0110] The excitation source 213 is magnetically coupled to the probe coupling circuit 209d in a manner similar as was mentioned with respect to the polyphase waveguide probe 200a (FIG. 7A) set forth above. To this end, the excitation source 213 is coupled to a coil L_P that acts as a primary and the coil L_{2d} acts as a secondary. Alternatively, the coil L_{1d} may act as a secondary as well.

[0111] In order to adjust the polyphase waveguide probe 200d for the excitation and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of each of the coils L_{1d} and L_{2d} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1d} or L_{2d}.

[0112] Referring now to FIG. 7E, shown is still another example of the polyphase waveguide probe 200 (FIG. 6), denoted herein as polyphase waveguide probe 200e, according to one embodiment. The polyphase waveguide probe 200e includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. The second medium 206 is above the lossy conducting medium 203. The charge terminals T_1 and T_2 are positioned along a vertical axis z to provide for cylindrical symmetry in the resulting Zenneck surface wave as was described above. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the

charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium 203.

[0113] The polyphase waveguide probe 200e also includes a probe coupling circuit 209e comprising a first coil L_{1e} and a resistor R_2. A first lead of the first coil L_{1e} is coupled to the charge terminal T_1, and the second lead of the first coil L_{1e} is coupled to the lossy conducting medium 203. A first lead of the resistor R_2 is coupled to the charge terminal T_2, and the second lead of the resistor R_2 is coupled to the lossy conducting medium 203.

[0114] The excitation source 213 is magnetically coupled to the probe coupling circuit 209e in a manner similar as was mentioned with respect to the polyphase waveguide probe 200a (FIG. 7A) set forth above. To this end, the excitation source 213 is coupled to a coil L_P that acts as a primary and the coil L_{1e} acts as a secondary.

[0115] In order to adjust the polyphase waveguide probe 200e for the transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of the coil L_{1e} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1e}. In addition, the magnitude of the resistance R_2 may be adjusted as well.

[0116] Referring now to FIG. 7F, shown is a further example of the polyphase waveguide probe 200 (FIG. 6), denoted herein as polyphase waveguide probe 200f, according to one embodiment. The polyphase waveguide probe 200f includes a charge terminal T_1 and a ground screen G that acts as a second charge terminal. The charge terminal T_1 and the ground screen G are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. The second medium 206 is above the lossy conducting medium 203. Note that to calculate the height h of the transmission structure, the height H_2 of the ground screen G is subtracted from the height H_1 of the charge terminal T_1.

[0117] The charge terminal T_1 has a self-capacitance C_1, and the ground screen G has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminal T_1 and the ground screen G, respectively, depending on the voltages applied to the charge terminal T_1 and the ground screen G at any given instant. A mutual capacitance C_M may exist between the charge terminal T_1 and the ground screen G depending on the distance there between. In addition, bound capacitances may exist between the charge terminal T_1 and/or the ground screen G and the lossy conducting medium 203 depending on the heights of the charge terminal T_1 and the ground screen G with respect to the lossy conducting medium 203. Generally, a bound capacitance will exist between the ground screen G and the lossy conducting medium 203 due to its proximity to the lossy conducting medium 203.

[0118] The polyphase waveguide probe 200f includes a probe coupling circuit 209f that is made up of an inductive impedance comprising a coil L_{1f} having a pair of leads that are coupled to the charge terminal T_1 and ground screen G. In one embodiment, the coil L_{1f} is specified to have an electrical length that is one-half (½) of the wavelength at the operating frequency of the polyphase waveguide probe 200f.

[0119] While the electrical length of the coil L_{1f} is specified as approximately one-half (½) the wavelength at the operating frequency, it is understood that the coil L_{1f} may be specified with an electrical length at other values. According to one embodiment, the fact that the coil L_{1f} has an electrical length of approximately one-half the wavelength at the operating frequency provides for an advantage in that a maximum voltage differential is created on the charge terminal T_1 and the ground screen G. Nonetheless, the length or diameter of the coil L_{1f} may be increased or decreased when adjusting the polyphase waveguide probe 200f to obtain optimal transmission of a Zenneck surface wave. Alternatively, it may be the case that the inductive impedance is specified to have an electrical length that is significantly less than or greater than ½ the wavelength at the operating frequency of the polyphase waveguide probe 200f.

[0120] According to one embodiment, the excitation source 213 is coupled to the probe coupling circuit 209f by way of magnetic coupling. Specifically, the excitation source 213 is coupled to a coil L_P that is inductively coupled to the coil L_{1f}. This may be done by link coupling, a phasor/coupling network, or other approach as can be appreciated. To this end, the coil L_P acts as a primary, and the coil L_{1f} acts as a secondary as can be appreciated.

[0121] In order to adjust the polyphase waveguide probe 200a for the launching and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium 203 and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of the coil L_{1f} may be altered by adding or eliminating turns or by changing some other dimension of the coil L_{1f}.

[0122] Referring now to FIG. 7G, shown is another example of the polyphase waveguide probe 200 (FIG. 6), denoted herein as polyphase waveguide probe 200g, according to one embodiment. The polyphase waveguide probe 200g includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium 203. The second medium 206 is above the lossy conducting medium 203. The charge terminals T_1 and T_2 are positioned along a vertical axis z to provide for cylindrical symmetry in the resulting Zenneck surface wave as was described above. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium 203 depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium 203.

[0123] The polyphase waveguide probe 200g also includes a probe coupling circuit 209g comprising a first coil L_{1g}, a second coil L_{2g}, and a variable capacitor C_V. The first coil L_{1g} is coupled to each of the charge terminals T_1 and T_2 as shown. The second coil L_{2g} has a first lead that is coupled to a variable capacitor C_V and a second lead that is coupled to the lossy

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conducting medium **203**. The variable capacitor C_V, in turn, is coupled to the charge terminal T_2 and the first coil L_{1g}.

[0124] The excitation source **213** is magnetically coupled to the probe coupling circuit **209g** in a manner similar as was mentioned with respect to the polyphase waveguide probe **200a** (FIG. 7A) set forth above. To this end, the excitation source **213** is coupled to a coil L_P that acts as a primary and either the coil L_{1g} or the coil L_{2g} may act as a secondary.

[0125] In order to adjust the polyphase waveguide probe **200g** for the launching and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium **203** and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of each of the coils L_{1g} and L_{2g} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1g} or L_{2g}. In addition, the variable capacitance C_V may be adjusted.

[0126] Referring now to FIG. 7H, shown is yet another example of the polyphase waveguide probe **200** (FIG. **6**), denoted herein as polyphase waveguide probe **200h**, according to one embodiment. The polyphase waveguide probe **200h** includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium **203**. The second medium **206** is above the lossy conducting medium **203**. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium **203** depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium **203**.

[0127] The polyphase waveguide probe **200h** also includes a probe coupling circuit **209h** comprising a first coil L_{1h} and a second coil L_{2h}. The first lead of the first coil L_{1h} is coupled to the charge terminal T_1, and the second lead of the first coil L_{1h} is coupled to the second charge terminal T_2. A first lead of the second coil L_{2h} is coupled to a terminal T_T, and the second lead of the second coil L_{2h} is coupled to the lossy conducting medium **203**. The terminal T_T is positioned relative to the charge terminal T_2 such that a coupling capacitance C_C exists between the charge terminal T_2 and the terminal T_T.

[0128] The excitation source **213** is magnetically coupled to the probe coupling circuit **209h** in a manner similar as was mentioned with respect to the polyphase waveguide probe **200a** (FIG. 7A) set forth above. To this end, the excitation source **213** is coupled to a coil L_P that acts as a primary and the coil L_{2h} acts as a secondary. Alternatively, the coil L_{1h} may act as a secondary as well.

[0129] In order to adjust the polyphase waveguide probe **200h** for the launching and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium **203** and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of each of the coils L_{1h} and L_{2h} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1h} or L_{2h}. Also the spacing between the

charge terminal T_2 and the terminal T_T may be altered, thereby modifying the coupling capacitance C_C as can be appreciated.

[0130] Referring now to FIG. 7I, shown is yet another example of the polyphase waveguide probe **200** (FIG. **6**), denoted herein as polyphase waveguide probe **200i**, according to one embodiment. The polyphase waveguide probe **200i** is very similar to the polyphase waveguide probe **200h** (FIG. 7H) except for the fact that the excitation source **213** is series-coupled to the probe coupling circuit **209i** as will be described.

[0131] To this end, the polyphase waveguide probe **200i** includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium **203**. The second medium **206** is above the lossy conducting medium **203**. The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium **203** depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium **203**.

[0132] The polyphase waveguide probe **200i** also includes a probe coupling circuit **209i** comprising a first coil L_{1i} and a second coil L_{2i}. The first lead of the first coil L_{1i} is coupled to the charge terminal T_1, and the second lead of the first coil L_{1i} is coupled to the second charge terminal T_2. A first lead of the second coil L_{2i} is coupled to a terminal T_T, and the second lead of the second coil L_{2i} is coupled to an output of the excitation source **213**. Also, a ground lead of the excitation source **213** is coupled to the lossy conducting medium **203**. The terminal T_T is positioned relative to the charge terminal T_2 such that a coupling capacitance C_C exists between the charge terminal T_2 and the terminal T_T.

[0133] The polyphase waveguide probe **200i** provides one example where the excitation source **213** is series-coupled to the probe coupling circuit **209i** as mentioned above. Specifically, the excitation source **213** is coupled between the coil L_{2i} and the lossy conducting medium **203**.

[0134] In order to adjust the polyphase waveguide probe **200i** for the launching and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium **203** and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of each of the coils L_{1i} and L_{2i} may be altered by adding or eliminating turns or by changing some other dimension of the respective coils L_{1i} or L_{2i}. Also the spacing between the charge terminal T_2 and the terminal T_T may be altered, thereby modifying the coupling capacitance C_C as can be appreciated.

[0135] Referring now to FIG. 7J, shown is an example of the polyphase waveguide probe **200** (FIG. **6**), denoted herein as polyphase waveguide probe **200j**, according to one embodiment. The polyphase waveguide probe **200j** includes the charge terminals T_1 and T_2 that are positioned along a vertical axis z that is substantially normal to the plane presented by the lossy conducting medium **203**. The second medium **206** is above the lossy conducting medium **203**. In

this embodiment, the charge terminal T_1 comprises a sphere and the charge terminal T_2 comprises a disk. In this respect, the polyphase waveguide probe **200***j* provides an illustration that the charge terminals T_N may comprise any shape.

[0136] The charge terminal T_1 has a self-capacitance C_1, and the charge terminal T_2 has a self-capacitance C_2. During operation, charges Q_1 and Q_2 are imposed on the charge terminals T_1 and T_2, respectively, depending on the voltages applied to the charge terminals T_1 and T_2 at any given instant. A mutual capacitance C_M may exist between the charge terminals T_1 and T_2 depending on the distance there between. In addition, bound capacitances may exist between the respective charge terminals T_1 and T_2 and the lossy conducting medium **203** depending on the heights of the respective charge terminals T_1 and T_2 with respect to the lossy conducting medium **203**.

[0137] The polyphase waveguide probe **200***j* includes a probe coupling circuit **209***j* comprising an inductive impedance comprising a coil L_{1j} having a pair of leads that are coupled to respective ones of the charge terminals T_1 and T_2. In one embodiment, the coil L_{1j} is specified to have an electrical length that is one-half (½) of the wavelength at the operating frequency of the polyphase waveguide probe **200***j*. While the electrical length of the coil L_{1j} is specified as approximately one-half (½) the wavelength at the operating frequency, it is understood that the coil L_{1j} may be specified with an electrical length at other values as was discussed with reference to the polyphase waveguide probe **200***a* (FIG. **7**A) described above. In addition, the probe coupling circuit **209***j* includes a tap **223** on the coil L_{1j} that is coupled to the lossy conducting medium **203**.

[0138] The excitation source **213** is magnetically coupled to the probe coupling circuit **209***j* in a manner similar as was mentioned with respect to the polyphase waveguide probe **200***a* (FIG. **7**A) set forth above. To this end, the excitation source **213** is coupled to a coil L_P that acts as a primary and the coil L_{1j} acts as a secondary. The coil L_P can be positioned at any location along the coil L_{1j}. Also, the coil L_P can be positioned above or below the tap **223**.

[0139] In order to adjust the polyphase waveguide probe **200***j* for the launching and transmission of a desired Zenneck surface wave, the heights of the respective charge terminals T_1 and T_2 may be altered with respect to the lossy conducting medium **203** and with respect to each other. Also, the sizes of the charge terminals T_1 and T_2 may be altered. In addition, the size of the coil L_{1j} may be altered by adding or eliminating turns or by changing some other dimension of the coil L_{1j}. Further, the position of the tap **223** on the coil L_{1j} may be adjusted.

[0140] With reference to the various embodiments of the polyphase waveguide probes **200***a*-*j* in FIGS. **7**A-J, each of the polyphase waveguide probes **200***a*-*j* may be excited to transmit energy conveyed in the form of a guided wave, or waveguide mode along the surface of the lossy conducting medium **203**. To facilitate such transmission, the elements of each of the polyphase waveguide probes **200***a*-*j* may be adjusted to impose a desired voltage magnitude and phase on the respective charge terminals T_1 and T_2 when the respective polyphase waveguide probe **200***a*-*j* is excited. Such excitation may occur by applying energy from an excitation source **213** to the respective polyphase waveguide probe **200***a*-*j* as was described above.

[0141] The voltage magnitudes and phases imposed on the charge terminals T_1 and T_2 may be adjusted in order to sub-

stantially synthesize the fields that are substantially mode-matched to the guided or Zenneck surface-waveguide mode of the lossy conducting medium **203** at the site of transmission given the local permittivity $\in_r$, conductivity a, and potentially other parameters of the lossy conducting medium **203**. The waveguide mode of the surface-guided wave is expressed in Equations (21), (22), and (23) set forth above. This surface-waveguide mode has a radial surface current density expressed in Equation (20) in Amperes per meter.

[0142] It is understood that it may be difficult to synthesize fields that exactly match the surface-waveguide mode expressed in Equations (21), (22), and (23) set forth above. However, a guided surface wave may be launched if such fields at least approximate the surface-waveguide mode. According to various embodiments, the fields are synthesized to match the surface-waveguide mode within an acceptable engineering tolerance so as to launch a guided surface wave.

[0143] Likewise, it may be difficult to synthesize a radial surface current density that exactly matches the radial surface current density of the Zenneck surface-waveguide mode, where the synthesized radial surface current density results from the synthesized fields described above. According to various embodiments, the polyphase waveguide probes **200** may be adjusted to match the radial surface current density of the guided surface-waveguide mode within an acceptable engineering tolerance so as to launch a Zenneck surface wave mode. By creating specific charge distributions plus their images at complex distances, the various polyphase waveguide probes **200***a*-*j* set forth above excite surface currents, the fields of which are designed to approximately match a propagating Zenneck surface wave mode and a Zenneck surface wave is launched. By virtue of this complex image technique inherent in the various polyphase waveguide probes **200***a*-*j* described above, one is able to substantially mode-match to the surface waveguide modes that the guiding interface wants to support at the location of transmission. The guiding interface is the interface between Region 1 (FIG. **2**) and Region 2 (FIG. **2**) as described above. According to one embodiment, the guiding interface is the interface between the lossy conducting medium **203** presented by the Earth and the atmospheric medium as described above.

[0144] When the voltage magnitudes and phases imposed on the charge terminals T_1 and T_2 are adjusted so that they, plus their effective images at complex depths, excite complex surface currents whose fields synthesize the fields that substantially match the Zenneck surface-waveguide mode of the lossy conducting medium **203** at the site of transmission, by virtue of the Leontovich boundary condition, such fields will automatically substantially synthesize a wave front incident at a complex Brewster angle of the lossy conducting medium **203**, resulting in zero reflection. This is the condition of wave matching at the boundary.

[0145] Referring next to FIGS. **8**A, **8**B, and **8**C, shown are examples of graphs **300***a*, **300***b*, and **300***c* that depict field strength in Volts per meter as a function of distance in kilometers for purposes of comparison between a Zenneck surface wave and conventionally radiated fields. In addition, the various graphs **300***a*, **300***b*, and **300***c* illustrate how the distance of transmission of a Zenneck surface wave varies with the frequency of transmission.

[0146] Each graph **300***a*, **300***b*, and **300***c* depicts a corresponding guided field strength curve **303***a*, **303***b*, and **303***c* and corresponding radiated field strength curves **306***a*, **306***b*, and **306***c*. The guided field strength curves **303***a*, **303***b*, and

303c were generated assuming various parameters. Specifically, the graphs **300a**, **300b**, and **300c** were calculated with a constant charge Q_1 (FIG. **3**) applied to the upper terminal T_1 (FIG. **3**) at frequencies of 10 MHz, 1 MHz, and 0.1 MHz, respectively. Constitutive parameters of $\in_r$=15 and σ=0.008 mhos/m, which are taken from the R-3 map for central Ohio set forth by the Federal Communications Commission (FCC), were assumed for purposes of calculation. The following table provides the assumed polyphase waveguide probe operating parameters for the generation of each of the guided field strength curve **303a**, **303b**, and **303c**.

Curve	Frequency (MHz)	λ	Height of Terminal T_1 (m)	H/λ	Self-Cap of Terminal T_1 (pF)	Voltage on Term T_1 (V)	Charge Q_1 (Coulombs)
303a	10	30	0.8	0.027	50	10,000	5×10^{-7}
303b	1.0	300	8	0.027	100	5,000	5×10^{-7}
303c	0.1	3000	8	0.0027	100	5,000	5×10^{-7}

[0147] In order to have physically realizable operation, the height of terminal T_1 was specified at H_{T1}=8 meters for f=0.1 MHz and 1.0 MHz, but shortened to 0.8 meters at 10 MHz in order to keep the current distribution uniform. Also, the self-capacitance C_1 of the terminal T_1 was set to 100 pF for operation at f=0.1 MHz and 1.0 MHz. This capacitance is unreasonably large for use at 10 MHz, so the self-capacitance C_1 was reduced for that case. However, the resulting terminal charge Q_{T1} which is the controlling parameter for field strength was kept at the same value for all three guided field strength curve **303a**, **303b**, and **303c**.

[0148] From the graphs it can be seen that the lower the frequency, the less the propagation attenuation and the fields reach out over greater distances. However, consistent with conservation of energy, the energy density decreases with distance. Another way to state that is that the higher the frequency, the smaller the region over which the energy is spread, so the greater the energy density. Thus, the "knee" of the Zenneck surface wave shrinks in range as the frequency is increased. Alternatively, the lower the frequency, the less the propagation attenuation and the greater the field strength of the Zenneck surface wave at very large distances from the site of transmission using a polyphase waveguide probe **200** (FIG. **6**).

[0149] The Zenneck surface wave for each case is identified as guided field strength curves **303a**, **303b**, and **303c**, respectively. The Norton ground wave field strength in Volts per meter for a short vertical monopole antenna, of the same height as the respective polyphase waveguide probe **200**, with an assumed ground loss of 10 ohms, is represented by the radiated field strength curves **306a**, **306b**, and **306c**, respectively. It is asserted that this is a reasonably realistic assumption for monopole antenna structures operating at these frequencies. The critical point is that a properly mode-matched polyphase waveguide probe launches a guided surface wave which dramatically outperforms the radiation field of any monopole at distances out to just beyond the "knee" in the guided field strength curves **303a-c** of the respective Zenneck surface waves.

[0150] Given the foregoing, according to one embodiment, the propagation distance of a guided surface wave varies as a function of the frequency of transmission. Specifically, the lower the transmission frequency, the less the exponential attenuation of the guided surface wave and, therefore, the

farther the guided surface wave will propagate. As mentioned above, the field strength of a guided surface wave falls off at a rate of

$$\frac{e^{-\alpha d}}{\sqrt{d}},$$

whereas the field strength of a radiated electromagnetic field falls off geometrically, proportional to 1/d, where d is the distance in kilometers. Thus, each of the guided field strength curves **303a**, **303b**, and **303c** feature a knee as was described above. As the frequency of transmission of a polyphase waveguide probe described herein decreases, the knee of the corresponding guided field strength curve **303a**, **303b**, and **303c** will push to the right in the graph.

[0151] FIG. **8A** shows a guided field strength curve **303a** and a radiated field strength curve **306a** generated at a frequency of 10 Megahertz. As shown, the guided surface wave falls off below 10 kilometers. In FIG. **8B**, the guided field strength curve **303b** and the radiated field strength curve **306b** are generated at a frequency of 1 Megahertz. The guided field strength curve **303b** falls off at approximately 100 Kilometers. Finally, in FIG. **8C**, the guided field strength curve **303c** and the radiated field strength curve **306c** are generated at a frequency of 100 Kilohertz (which is 0.1 Megahertz). The guided field strength curve **303c** falls off at between 4000-7000 Kilometers.

[0152] Note that if the frequency is low enough, it may be possible to transmit a guided surface wave around the entire Earth. It is believed that such frequencies may be at or below approximately 20-25 kilohertz. It should be noted that at such low frequencies, the lossy conducting medium **203** (FIG. **6**) ceases to be a plane and becomes a sphere. Thus, when a lossy conducting medium **203** comprises a terrestrial medium, the calculation of guided field strength curves will be altered to take into account the spherical shape at low frequencies where the propagation distances approach size of the terrestrial medium.

[0153] Given the foregoing, next some general guidance is provided in constructing a polyphase waveguide probe **200** (FIG. **6**) using the terrestrial medium of Earth as the lossy conducting medium **203** according to the various embodiments. As a practical approach, one might specify the frequency of operation and identify the desired field strength of the guided surface wave at a distance of interest from the respective polyphase waveguide probe **200** to be constructed.

[0154] Given these parameters, next one may determine the charge Q_1 (FIG. **6**) that is to be imposed on the upper charge terminal T_1 (FIG. **6**) in order to produce the desired field strength at the specified distance. To determine the charge Q_1 needed, one would need to obtain the permittivity $\in_r$ and the conductivity a of the Earth at the transmission site. These values can be obtained by measurement or by reference to

conductivity charts published, for example, by the Federal Communications Commission or the Committee Consultif International Radio (CCIR). When the permittivity $\in_r$, conductivity σ, and the desired field strength at the specified distance are known, the needed charge Q_1 can be determined by direct calculation of the field strength from Zenneck's exact expressions set forth in Equations (21)-(23) above.

[0155] Once the needed charge Q_1 is determined, next one would need to identify what self-capacitance C_1 of the charge terminal T_1 at what voltage V would produce the needed charge Q_1 on the charge terminal T_1. A charge Q on any charge terminal T is calculated as Q=CV. In one approach, one can choose what is deemed to be an acceptable voltage V that can be placed on the charge terminal T_1, and then construct the charge terminal T_1 so as to have the required self-capacitance C_1 to achieve the needed charge Q_1. Alternatively, in another approach, one could determine what is an achievable self-capacitance C_1 by virtue of the specific construction of the charge terminal T_1, and then raise the resulting charge terminal T_1 to the required voltage V to achieve the needed charge Q_1.

[0156] In addition, there is an issue of operational bandwidth that should be considered when determining the needed self-capacitance C_1 of the charge terminal T_1 and voltage V to be imposed on the charge terminal T_1. Specifically, the bandwidth of the polyphase waveguide probes 200 described herein is relatively large. This results in a significant degree of flexibility in specifying the self-capacitance C_1 or the voltage V as described above. However, it should be understood that as the self-capacitance C_1 is reduced and the voltage V increased, the bandwidth of the resulting polyphase waveguide probe 200 will diminish.

[0157] Experimentally, it should be noted that a smaller self-capacitance C_1 may make a given polyphase waveguide probe 200 more sensitive to small variations in the permittivity $\in_r$ or conductivity σ of the Earth at or near the transmission site. Such variation in the permittivity $\in_r$ or conductivity σ might occur due to variation in the climate given the transition between the seasons or due to changes in local weather conditions such as the onset of rain, drought, and/or other changes in local weather. Consequently, according to one embodiment, the charge terminal T_1 may be specified so as to have a relatively large self-capacitance C_1 as is practicable.

[0158] Once the self-capacitance C_1 of the charge terminal T_1 and the voltage to be imposed thereon are determined, next the self-capacitance C_2 and physical location of the second charge terminal T_2 are to be determined. As a practical matter, it has been found easiest to specify the self-capacitance C_2 of the charge terminal T_2 to be the same as the self-capacitance C_1 of the charge terminal T_1. This may be accomplished by making the size and shape of the charge terminal T_2 the same as the size and shape of the charge terminal T_1. This would ensure that symmetry is maintained and will avoid the possibility of unusual phase shifts between the two charge terminals T_1 and T_2 that might negatively affect achieving a match with the complex Brewster angle as described above. The fact that the self-capacitances C_1 and C_2 are the same for both charge terminals T_1 and T_2 will result in the same voltage magnitudes on the charge terminals T_1 and T_2. However, it is understood that the self-capacitances C_1 and C_2 may differ, and the shape and size of the charge terminals T_1 and T_2 may differ.

[0159] To promote symmetry, the charge terminal T_2 may be positioned directly under the charge terminal T_1 along the vertical axis z (FIG. 6) as described above. Alternatively, it may be possible to position the charge terminal T_2 at some other location with some resulting effect.

[0160] The distance between the charge terminals T_1 and T_2 should be specified so as to provide for the best match between the fields generated by the polyphase waveguide probe 200 and the guided surface-waveguide mode at the site of transmission. As a suggested starting point, this distance may be set so that the mutual capacitance C_M (FIG. 6) between the charge terminals T_1 and T_2 is the same or less than the isolated capacitance C_1 on the charge terminal T_1. Ultimately, one should specify the distance between the charge terminals T_1 and T_2 to make the mutual capacitance C_M as small as is practicable. The mutual capacitance C_M may be determined by measurement, and the charge terminals T_1 and T_2 may be positioned accordingly.

[0161] Next, the proper height $h=H_1-H_2$ (FIGS. 7A-J) of the polyphase waveguide probe 200 is determined. The so-called "image complex-depth" phenomenon comes into bearing here. This would entail consideration of the superposed fields on the surface of the Earth from the charge reservoirs T_1 and T_2 that have charges Q_1 and Q_2, and from the subsurface images of the charges Q_1 and Q_2 as height h is varied. Due to the significant number of variables to consider to ensure that a given polyphase waveguide probe 200 is mode matched with the guided surface-waveguide mode of the Earth at the site of transmission, a practical starting point is a height h at which the bound capacitance of each of the charge reservoirs T_1 and T_2 with respect to the ground is negligible such that the capacitance associated with the charge terminals T_1 and T_2 is essentially their isolated self-capacitance C_1 and C_2, respectively.

[0162] Another consideration to take into account when determining the height h associated with a polyphase waveguide probe 200 is whether radiation is to be avoided. Specifically, as the height h of the polyphase waveguide probe 200 approaches an appreciable portion of a wavelength at the frequency of operation, the radiation resistance R_r will grow quadratically with height h and radiation will begin to dominate over the generation of a guided surface wave as described above. One benchmark set forth above that ensures the Zenneck surface wave will dominate over any radiation is to make sure the height h is less than 10% of the wavelength at the frequency of operation, although other benchmarks may be specified. In some cases, it may be desired to allow some degree of radiation to occur in addition to launching a guided surface wave, where the height h may be specified accordingly.

[0163] Next, the probe coupling circuit 209 (FIG. 6) is specified to provide for the voltage phase between the charge terminals T_1 and T_2. The voltage phase appears to have a significant effect on creating fields that mode-match the guided surface-waveguide mode at the site of transmission. Assuming that the placement of the charge terminals T_1 and T_2 is along the vertical z axis to promote symmetry, the probe coupling circuit 209 may be specified to provide for a voltage phase differential of 180 degrees on the charge terminals T_1 and T_2. That is to say, the probe coupling circuit 209 is specified so that voltage V on the charge terminal T_1 is 180 degrees out of phase with respect to the voltage on the charge terminal T_2.

[0164] As was described above, one example approach is to place a coil L_{1a} (FIG. 7A) between the charge terminals T_1 and T_2 as described above with reference to the polyphase

waveguide probe **200a** and adjust the coil L_{1a} until the resulting system is electrically half-wave resonant. This would place a voltage V on the charge terminal T_1 and voltage –V on the charge terminal T_2 such that the largest voltages are placed on the charge terminals T_1 and T_2 180 degrees out of phase.

[0165] The excitation source **213** (FIG. **6**) may then be coupled to the probe coupling circuit **209** and the output voltage adjusted to achieve the required voltage V to provide for the needed charge Q_1 as described above. The excitation source **213** may be coupled via magnetic coupling, capacitive coupling, or conductive coupling (direct) to the probe coupling circuit **209**. Note that the output of the excitation source **213** may be stepped up using a transformer or via some other approach if necessary. The location of the coil L_{1a} can be at any location such as down on the ground by the excitation source **213**. Alternatively, as per best RF practice, the coil L_{1a} can be positioned directly between the charge reservoirs T_1 and T_2. Principles of impedance matching may be applied when coupling the excitation source **213** to the probe coupling circuit **209**.

[0166] Note that the phase differential does not necessarily have to be 180 degrees. To this end, one has the option of raising and lowering one or both of the charge terminals T_1 and/or T_2, adjusting the voltages V on the charge terminals T_1 and/or T_2, or adjusting the probe coupling circuit **209** to adjust the voltage magnitudes and phases to create fields that most closely match the guided surface-waveguide mode in order to generate a guided surface wave.

Experimental Results

[0167] The above disclosures are supported by experimental measurements and documentation. With reference to FIG. **9**, shown is a graph that presents the measured field strength of an electromagnetic field transmitted by one embodiment of an experimental polyphase waveguide probe measured on Oct. 14, 2012 in Plymouth, N.H. The frequency of transmission was 59 MHz with a voltage of 60 mV imposed on the charge terminal T_1 of the experimental polyphase waveguide probe. The self-capacitance C_1 of the experimental polyphase waveguide probe was 8.5 pF. The conductivity σ of the ground at the test site is 0.0002 mhos/m, and the permittivity $\in_r$ of the ground at the test site was 5. These values were measured in situ at the frequency in use.

[0168] The graph includes a guided field strength curve **400** that is labeled a "Zenneck" curve at 80% efficiency and a radiated field strength curve **403** that is labeled a "Norton" curve at 100% radiation efficiency, which is the best possible. To this end, the radiated field strength curve **403** represents the radiated electromagnetic fields that would be generated by a ¼ wavelength monopole antenna operating at a frequency of 59 MHz. The circles **406** on the graph represent measured field strengths produced by the experimental polyphase waveguide probe. The field strength measurements were performed with a NIST-traceable Potomac Instruments FIM-71 commercial VHF field strength meter. As can be seen, the measured field strengths fall along the theoretical guided field strength curve **400**. These measured field strengths are consistent with the propagation of a guided or Zenneck surface wave.

[0169] Referring next to FIG. **10**, shown is a graph that presents the measured phase of the transmitted electromagnetic wave from the experimental polyphase waveguide probe. The curve J(r) indicates the phase of the fields incident to the currents J_1 and J_2 with a transition between the currents

J_1 and J_2 as shown. The curve **503** indicates the asymptote depicting the phase of the current J_1, and the curve **506** indicates the asymptote depicting the phase of the current J_2. A difference of approximately 45 degrees generally exists between the phases of the respective currents J_1 and J_2. The circles **509** indicate measurements of the phase of the current J(r) generated by the experimental polyphase waveguide probe operating at 59 MHz as with FIG. **9**. As shown, the circles **509** fall along the curve J(r) indicating that there is a transition of the phase of the current J(r) from the curve **503** to the curve **506**. This indicates that the phase of the current J(r) generated by the experimental polyphase waveguide probe transitions from the phase generated by the close-in current J_1 to the far-out current J_2. Thus, these phase measurements are consistent with the phase with the presence of a guided or Zenneck surface wave.

[0170] With reference to FIG. **11** shown is a graph of a second set of measured data that depicts the field strength of an electromagnetic field transmitted by a second embodiment of an experimental polyphase waveguide probe measured on Nov. 1, 2003 in the vicinity of Ashland, N.H. and across the region north of Lake Winnipesaukee. The frequency of transmission was 1850 kHz with a voltage of 1250 V imposed on the charge terminal T_1 of the experimental polyphase waveguide probe. The experimental polyphase waveguide probe had a physical height of H_1=2 meters. The self-capacitance C_1 of the experimental polyphase waveguide probe in this experiment, which was a flat conducting disk of 1 meter radius, was measured to be 70 pF. The polyphase waveguide probe was arranged as illustrated in FIG. **7J**, with spacing h=1 meter and the height of the charge terminal T_2 above the ground (the lossy conducting medium **203**) being H_2=1 meter. The average conductivity a of the ground in the vicinity of experimentation was 0.006 mhos/m, and the relative permittivity $\in_r$ of the ground was on the order of 15. These were determined at the frequency in use.

[0171] The graph includes a guided field strength curve **600** that is launched by the experimental polyphase waveguide probe, labeled as "Zenneck" curve at 85% efficiency, and a radiated field strength curve **603** that is labeled a "Norton" curve as radiated from a resonated monopole of the same height, H_2=2 meters, over a ground screen composed of 20 radial wires equally spaced and of length 200 feet each. To this end, the radiated field strength curve **603** represents the conventional Norton ground wave field radiated from a conventional stub monopole antenna operating at a frequency of 1850 kHz over the lossy Earth. The circles **606** on the graph represent measured field strengths produced by the experimental polyphase waveguide probe.

[0172] As can be seen, the measured field strengths fall closely along the theoretical Zenneck guided field strength curve **600**. Special mention of the field strength measured at the r=7 mile point may be made. This field strength data point was measured adjacent to the shore of a lake, and this may account for the data departing slightly above the theoretical Zenneck guided field strength curve **600**, i.e. the constitutive parameters, $\in_r$ and/or σ, at that location are likely to have departed significantly from the path-average constitutive parameters.

[0173] The field strength measurements were performed with a NIST-traceable Potomac Instruments FIM-41 MF/HF field strength meter. The measured field strength data are consistent with the presence of a guided or Zenneck surface wave. It is apparent from the experimental data that the mea-

sured field strengths observed at distances less than 15 miles could not possibly be due to conventional Norton ground wave propagation, and can only be due to guided surface wave propagation launched by the polyphase probe operating as disclosed above. Under the given 1.85 MHz experimental conditions, out at 20 miles it appears that a Norton ground wave component has finally overtaken the Zenneck surface wave component.

[0174] A comparison of the measured Zenneck surface wave data shown in FIG. 9 at 59 MHz with the measured data in FIG. 11 at 1.85 MHz illustrates the great advantage of employing a polyphase waveguide probe according to the various embodiments at lower frequencies.

[0175] These experimental data confirm that the present polyphase waveguide probes, comprising a plurality of appropriately phased and adjusted charge terminals, as taught herein, induce a phase-advanced surface current with a unique phase boost of $\arg(\sqrt{\gamma})$, and whose fields synthesize surface illumination at the complex Brewster angle for the lossy boundary as disclosed herein. The consequence is the efficient launching of cylindrical Zenneck-like wave propagation, guided by the boundary surface as an evanescent, single-conductor radial transmission-line mode, which attenuates as not as

$$\frac{e^{-\alpha d}}{\sqrt{d}},$$

not as a radiation field, which would decrease as 1/d due to geometrical spreading.

[0176] Referring next to FIGS. 12A, 12B, and 13, shown are examples of generalized receive circuits for using the surface-guided waves in wireless power delivery systems. FIGS. 12A and 12B include a linear probe 703 and a tuned resonator 706. FIG. 13 is a magnetic coil 709 according to various embodiments of the present disclosure. According to various embodiments, each one of the linear probe 703, the tuned resonator 706, and the magnetic coil 709 may be employed to receive power transmitted in the form of a guided surface wave on the surface of a lossy conducting medium 203 (FIG. 6) according to various embodiments. As mentioned above, in one embodiment the lossy conducting medium 203 comprises a terrestrial medium.

[0177] With specific reference to FIG. 12A, the open-circuit terminal voltage at the output terminals 713 of the linear probe 703 depends upon the effective height of the linear probe 703. To this end, the terminal point voltage may be calculated as

$$V_T = \int_0^{h_e} E_{inc} \cdot dl, \qquad (43)$$

where E_{inc} is the strength of the electric field in vector on the linear probe 703 in Volts per meter, dl is an element of integration along the direction of the linear probe 703, and h_e is the effective height of the linear probe 703. An electrical load 716 is coupled to the output terminals 713 through an impedance matching network 719.

[0178] When the linear probe 703 is subjected to a guided surface wave as described above, a voltage is developed across the output terminals 713 that may be applied to the electrical load 716 through a conjugate impedance matching network 719 as the case may be. In order to facilitate the flow of power to the electrical load 716, the electrical load 716

should be substantially impedance matched to the linear probe 703 as will be described below.

[0179] Referring to FIG. 12B, the tuned resonator 706 includes a charge terminal T_R that is elevated above the lossy conducting medium 203. The charge terminal T_R has a self-capacitance C_R. In addition, there may also be a bound capacitance (not shown) between the charge terminal T_R and the lossy conducting medium 203 depending on the height of the charge terminal T_R above the lossy conducting medium 203. The bound capacitance should preferably be minimized as much as is practicable, although this may not be entirely necessary in every instance of a polyphase waveguide probe 200.

[0180] The tuned resonator 706 also includes a coil L_R. One end of the coil L_R is coupled to the charge terminal T_R, and the other end of the coil L_R is coupled to the lossy conducting medium 203. To this end, the tuned resonator 706 (which may also be referred to as tuned resonator L_R-C_R) comprises a series-tuned resonator as the charge terminal C_R and the coil L_R are situated in series. The tuned resonator 706 is tuned by adjusting the size and/or height of the charge terminal T_R, and/or adjusting the size of the coil L_R so that the reactive impedance of the structure is substantially eliminated.

[0181] For example, the reactance presented by the self-capacitance C_R is calculated as

$$\frac{1}{j\omega C_R}.$$

Note that the total capacitance of the tuned resonator 706 may also include capacitance between the charge terminal T_R and the lossy conducting medium 203, where the total capacitance of the tuned resonator 706 may be calculated from both the self-capacitance C_R and any bound capacitance as can be appreciated. According to one embodiment, the charge terminal T_R may be raised to a height so as to substantially reduce or eliminate any bound capacitance. The existence of a bound capacitance may be determined from capacitance measurements between the charge terminal T_R and the lossy conducting medium 203.

[0182] The inductive reactance presented by a discrete-element coil L_R may be calculated as $j\omega L$, where L is the lumped-element inductance of the coil L_R. If the coil L_R is a distributed element, its equivalent terminal-point inductive reactance may be determined by conventional approaches. To tune the tuned resonator 706, one would make adjustments so that the inductive reactance presented by the coil L_R equals the capacitive reactance presented by the tuned resonator 706 so that the resulting net reactance of the tuned resonator 706 is substantially zero at the frequency of operation. An impedance matching network 723 may be inserted between the probe terminals 721 and the electrical load 726 in order to effect a conjugate-match condition for maxim power transfer to the electrical load 726.

[0183] When placed in the presence of a guided surface wave, generated at the frequency of the tuned resonator 706 and the conjugate matching network 723, as described above, maximum power will be delivered from the surface guided wave to the electrical load 726. That is, once conjugate impedance matching is established between the tuned resonator 706 and the electrical load 726, power will be delivered from the structure to the electrical load 726. To this end, an electrical load 726 may be coupled to the tuned resonator 706

by way of magnetic coupling, capacitive coupling, or conductive (direct tap) coupling. The elements of the coupling network may be lumped components or distributed elements as can be appreciated. In the embodiment shown in FIG. **12**B, magnetic coupling is employed where a coil L_S is positioned as a secondary relative to the coil L_R that acts as a transformer primary. The coil L_S may be link coupled to the coil L_R by geometrically winding it around the same core structure and adjusting the coupled magnetic flux as can be appreciated. In addition, while the tuned resonator **706** comprises a series-tuned resonator, a parallel-tuned resonator or even a distributed-element resonator may also be used.

[0184] Referring to FIG. **13**, the magnetic coil **709** comprises a receive circuit that is coupled through an impedance coupling network **733** to an electrical load **736**. In order to facilitate reception and/or extraction of electrical power from a guided surface wave, the magnetic coil **709** may be positioned so that the magnetic flux of the guided surface wave, H_ϕ, passes through the magnetic coil **709**, thereby inducing a current in the magnetic coil **709** and producing a terminal point voltage at its output terminals **729**. The magnetic flux of the guided surface wave coupled to a single turn coil is expressed by

$$\Psi = \iint_{A_{CS}} \mu_r \mu_o \vec{H} \cdot \hat{n} dA \qquad (44)$$

where ψ is the coupled magnetic flux, μ_r is the effective relative permeability of the core of the magnetic coil **709**, μ_o is the permeability of free space, H is the incident magnetic field strength vector, n is a unit vector normal to the cross-sectional area of the turns, and A_{CS} is the area enclosed by each loop. For an N-turn magnetic coil **709** oriented for maximum coupling to an incident magnetic field that is uniform over the cross-sectional area of the magnetic coil **709**, the open-circuit induced voltage appearing at the output terminals **729** of the magnetic coil **709** is

$$V = -N\frac{d\Psi}{dt} \approx -j\omega\mu_r\mu_0 HA_{CS}, \qquad (45)$$

where the variables are defined above. The magnetic coil **709** may be tuned to the guided wave frequency either as a distributed resonator or with an external capacitor across its output terminals **729**, as the case may be, and then impedance-matched to an external electrical load **736** through a conjugate impedance matching network **733**.

[0185] Assuming that the resulting circuit presented by the magnetic coil **709** and the electrical load **736** are properly adjusted and conjugate impedance matched, via impedance matching network **733**, then the current induced in the magnetic coil **709** may be employed to optimally power the electrical load **736**. The receive circuit presented by the magnetic coil **709** provides an advantage in that it does not have to be physically connected to the ground.

[0186] With reference to FIGS. **12**A, **12**B, and **13**, the receive circuits presented by the linear probe **703**, the tuned resonator **706**, and the magnetic coil **709** each facilitate receiving electrical power transmitted from any one of the embodiments of polyphase waveguide probes **200** described above. To this end, the energy received may be used to supply power to an electrical load **716/726/736** via a conjugate matching network as can be appreciated. This contrasts with the signals that may be received in a receiver that were transmitted in the form of a radiated electromagnetic field. Such

signals have very low available power and receivers of such signals do not load the transmitters.

[0187] It is also characteristic of the present guided surface waves generated using the polyphase waveguide probes **200** described above that the receive circuits presented by the linear probe **703**, the tuned resonator **706**, and the magnetic coil **709** will load the excitation source **213** (FIG. **3**) that is applied to the polyphase waveguide probe **200**, thereby generating the guided surface wave to which such receive circuits are subjected. This reflects the fact that the guided surface wave generated by a given polyphase waveguide probe **200** described above comprises a transmission line mode. By way of contrast, a power source that drives a radiating antenna that generates a radiated electromagnetic wave is not loaded by the receivers, regardless of the number of receivers employed.

[0188] Thus, together a given polyphase waveguide probe **200** and receive circuits in the form of the linear probe **703**, the tuned resonator **706**, and/or the magnetic coil **709** can together make up a wireless distribution system. Given that the distance of transmission of a guided surface wave using a polyphase waveguide probe **200** as set forth above depends upon the frequency, it is possible that wireless power distribution can be achieved across wide areas and even globally.

[0189] The conventional wireless-power transmission/distribution systems extensively investigated today include "energy harvesting" from radiation fields and also sensor coupling to inductive or reactive near-fields. In contrast, the present wireless-power system does not waste power in the form of radiation which, if not intercepted, is lost forever. Nor is the presently disclosed wireless-power system limited to extremely short ranges as with conventional mutual-reactance coupled near-field systems. The wireless-power system disclosed herein probe-couples to the novel surface-guided transmission line mode, which is equivalent to delivering power to a load by a wave-guide or a load directly wired to the distant power generator. Not counting the power required to maintain transmission field strength plus that dissipated in the surface waveguide, which at extremely low frequencies is insignificant relative to the transmission losses in conventional high-tension power lines at 60 Hz, all the generator power goes only to the desired electrical load. When the electrical load demand is terminated, the source power generation is relatively idle.

[0190] Referring next to FIG. **14**A shown is a schematic that represents the linear probe **703** and the tuned resonator **706**. FIG. **14**B shows a schematic that represents the magnetic coil **709**. The linear probe **703** and the tuned resonator **706** may each be considered a Thevenin equivalent represented by an open-circuit terminal voltage source V_S and a dead network terminal point impedance Z_S. The magnetic coil **709** may be viewed as a Norton equivalent represented by a short-circuit terminal current source I_S and a dead network terminal point impedance Z_S. Each electrical load **716/726/736** (FIGS. **12**A-B and FIG. **13**) may be represented by a load impedance Z_L. The source impedance Z_S comprises both real and imaginary components and takes the form $Z_S = R_S + jX_S$.

[0191] According to one embodiment, the electrical load **716/726/736** is impedance matched to each receive circuit, respectively. Specifically, each electrical load **716/726/736** presents through a respective impedance matching network **719/723/733** a load on the probe network specified as Z_L' expressed as $Z_L' = R_L' + j X_L'$, which will be equal to $Z_L' = Z_S* = R_S - j X_S$, where the presented load impedance Z_L' is the complex conjugate of the actual source impedance Z_S.

The conjugate match theorem, which states that if, in a cascaded network, a conjugate match occurs at any terminal pair then it will occur at all terminal pairs, then asserts that the actual electrical load **716/726/736** will also see a conjugate match to its impedance, Z_L'. See Everitt, W. L. and G. E. Tanner, *Communication Engineering*, McGraw-Hill, 3rd edition, 1956, p. 407. This ensures that the respective electrical load **716/726/736** is impedance matched to the respective receive circuit and that maximum power transfer is established to the respective electrical load **716/726/736**.

[0192] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims. In addition, all optional and preferred features and modifications of the described embodiments and dependent claims are usable in all aspects of the disclosure taught herein. Furthermore, the individual features of the dependent claims, as well as all optional and preferred features and modifications of the described embodiments are combinable and interchangeable with one another.

Therefore, the following is claimed:

1. A method, comprising the step of:
   positioning a receive circuit relative to a terrestrial medium; and
   receiving, via the receive circuit, energy conveyed in a form of a Zenneck surface wave on a surface of the terrestrial medium.

2. The method of claim **1**, wherein the receive circuit loads an excitation source coupled to a polyphase waveguide probe that generates the Zenneck surface wave.

3. The method of claim **1**, wherein the energy further comprises electrical power, and the method further comprises the step of applying the electrical power to an electrical load coupled to the receive circuit, where the electrical power is used as a power source for the electrical load.

4. The method of claim **1**, further comprising the step of impedance matching an electrical load to the receive circuit.

5. The method of claim **4**, further comprising the step of establishing a maximum power transfer from the receive circuit to the electrical load.

6. The method of claim **1**, wherein the receive circuit further comprises a magnetic coil.

7. The method of claim **1**, wherein the receive circuit further comprises a linear probe.

8. The method of claim **1**, wherein the receive circuit further comprises a tuned resonator coupled to the terrestrial medium.

9. An apparatus, comprising:
   a receive circuit that receives energy conveyed in a form of a Zenneck surface wave along a surface of a terrestrial medium.

10. The apparatus of claim **9**, wherein the receive circuit is configured to load an excitation source coupled to a polyphase waveguide probe that generates the Zenneck surface wave.

11. The apparatus of claim **9**, wherein the energy further comprises electrical power, and the receive circuit is coupled to an electrical load, and wherein the electrical power is applied to the electrical load, the electrical power being employed as a power source for the electrical load.

12. The apparatus of claim **11**, wherein the electrical load is impedance matched with the receive circuit.

13. The apparatus of claim **9**, wherein the receive circuit further comprises a magnetic coil.

14. The apparatus of claim **9**, wherein the receive circuit further comprises a linear probe.

15. The apparatus of claim **9**, wherein the receive circuit further comprises a tuned resonator.

16. The apparatus of claim **15**, wherein the tuned resonator comprises a series tuned resonator.

17. The apparatus of claim **15**, wherein the tuned resonator comprises a parallel tuned resonator.

18. The apparatus of claim **15**, wherein the tuned resonator comprises a distributed tuned resonator.

19. A power transmission system, comprising:
   a polyphase waveguide probe that transmits electrical energy in a form of a guided surface wave along a surface of a terrestrial medium; and
   a receive circuit that receives the electrical energy.

20. The power transmission system of claim **19**, wherein the receive circuit loads the polyphase waveguide probe.

21. The power transmission system of claim **19**, wherein an electrical load is coupled to the receive circuit and the electrical energy is used as a power source for the electrical load.

22. The power transmission system of claim **21**, wherein the electrical load is impedance matched to the receive circuit.

23. The power transmission system of claim **21**, wherein a maximum power transfer is established from the receive circuit to the electrical load.

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