# EXCITATION AND USE OF GUIDED SURFACE WAVE MODES ON LOSSY MEDIA

## CROSS REFERENCE TO RELATED CASES

**[0001]** This Patent Cooperation Treaty Application claims priority to and the benefit of both U.S. Patent Application Number 13/789,525 entitled "EXCITATION AND USE OF GUIDED SURFACE WAVE MODES ON LOSSY MEDIA" filed on March 7, 2013, and U.S. Patent Application Number 13/789,538 entitled "EXCITATION AND USE OF GUIDED SURFACE WAVE MODES ON LOSSY MEDIA" filed on March 7, 2013, both of which are incorporated herein by reference in their entirety.

## BACKGROUND

**[0002]** 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.

## SUMMARY OF INVENTION

[0002a] According to a first aspect of the present invention, there is provided a method, comprising: arranging a plurality of charge terminals of a polyphase waveguide probe above a lossy conducting medium, where the plurality of charge terminals are coupled to an excitation source; exciting the plurality of charge terminals via the excitation source, the excitation generating electromagnetic fields which are substantially mode-matched to a Zenneck surface wave mode of the lossy conducting medium; and transmitting energy in a form of a guided surface wave along a surface of the lossy conducting medium generated by the polyphase waveguide probe in the Zenneck surface wave mode.

[0002b] According to a second aspect of the present invention, there is provided an apparatus, comprising: a polyphase waveguide probe formed of a plurality of charge terminals positioned above a lossy conducting medium; and an excitation source coupled to the plurality of charge terminals, where the excitation source is operable to excite the plurality of charge terminals generating a plurality of electromagnetic fields which are substantially mode-matched to a Zenneck surface wave mode on a surface of the lossy conducting medium.

[0002c] According to a third aspect of the present invention, there is provided a method, comprising: positioning a receive circuit above a surface of a terrestrial medium; and receiving, via the receive circuit, energy transmitted from a polyphase waveguide probe in a form of a Zenneck surface wave along the surface of the terrestrial medium.

[0002d] According to a fourth aspect of the present invention, there is provided an apparatus, comprising: a receive circuit operable to receive energy transmitted from a polyphase waveguide probe in a form of a Zenneck surface wave along a surface of a lossy conducting medium when the receive circuit is positioned above the lossy conducting medium.

[0002e] According to a fifth aspect of the present invention, there is provided a power transmission system, comprising: a polyphase waveguide probe formed of a plurality of charge terminals positioned relative to a lossy conducting medium; an excitation source coupled to the plurality of charge terminals, wherein the excitation source is operable to excite the plurality of charge terminals, the excitation of the plurality of charge terminals generating a plurality of electromagnetic fields which are substantially mode-matched to a Zenneck surface wave mode on a surface of the lossy conducting medium; and a receive circuit operable to receive electrical energy from the polyphase waveguide probe via a guided surface wave along the surface of the lossy conducting medium.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0003]** 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.

**[0004]** 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.

**[0005]** 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.

**[0006]** 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.

**[0007]** 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.

## CLAIMS

Therefore, the following is claimed:

1. A method, comprising ~~the step of~~:

arranging a plurality of charge terminals of a polyphase waveguide probe above a lossy conducting medium, where the plurality of charge terminals are coupled to an excitation source;

exciting the plurality of charge terminals via the excitation source, the excitation generating electromagnetic fields which are substantially mode-matched to a Zenneck surface wave mode of the lossy conducting medium; and

transmitting energy ~~conveyed~~ in a form of a guided surface wave ~~surface-waveguide mode~~ along a surface of ~~a terrestrial~~ the lossy conducting medium generated by ~~exciting a~~ the polyphase waveguide probe in the Zenneck surface wave mode.

2. The method of claim 1, wherein the ~~step of transmitting energy conveyed in the form of the guided surface-waveguide mode along the surface of the terrestrial medium by exciting the polyphase waveguide probe further comprises the step of synthesizing~~ excitation of the plurality of charge terminals synthesizes a plurality of fields, the plurality of fields ~~that~~ substantially matching the Zenneck surface waveguide ~~guided surface-waveguide~~ mode of the ~~terrestrial~~ lossy conducting medium, wherein the arrangement of the plurality of charge terminals causes the plurality of fields ~~substantially to~~ synthesize a wave front incident at a complex Brewster angle of the ~~terrestrial~~ lossy conducting medium, resulting in a negligible reflection.

3. An apparatus, comprising:

a polyphase waveguide probe formed of a plurality of charge terminals positioned above a lossy conducting medium; and

an excitation source coupled to the plurality of charge terminals, where the excitation source is operable to excite the plurality of charge terminals generating ~~configured to create~~ a plurality of ~~resultant~~ electromagnetic fields ~~that~~ which are substantially mode-matched to a Zenneck surface wave mode on a surface of ~~a~~ the lossy conducting medium.

4. The apparatus of claim 3, wherein the lossy conducting medium ~~further comprises~~ is or includes a terrestrial medium.

5. The apparatus of any one of claims 3 or 4, wherein the excitation source and the plurality of charge terminals are configured such that a radiation resistance of the polyphase waveguide probe is substantially zero.

6. The apparatus of any one of claims 3-5, wherein a height of the polyphase waveguide probe above the surface of the lossy conducting medium is less than $\frac{\lambda}{2\pi}$ at an operating frequency of the polyphase waveguide probe, where $\lambda$ is a wavelength at the operating frequency.

7. The apparatus of any one of claims 3-6, wherein the arrangement and excitation of the plurality of charge terminals causes the electromagnetic ~~resultant~~ fields to substantially synthesize a wave front incident at a complex Brewster angle of the lossy conducting medium, resulting in substantially zero reflection.

~~8. The apparatus of any one of claims 3-7, wherein an excitation source is electrically coupled to the polyphase waveguide probe.~~

98. The apparatus of any one of claims 3-87, wherein a radial surface current density of the Zenneck surface wave mode is substantially expressed by

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

where γ is a surface wave radial propagation constant given by $\gamma = j\sqrt{k_o^2 + u_2^2}$ and $u_2$ is a vertical propagation constant given by $u_2 = \frac{-jk_o}{\sqrt{1 + (\varepsilon_r - jx)}}$, where $x = \frac{\sigma}{\omega \varepsilon_o}$, $\sigma$ is a conductivity of the lossy conducting medium, $\omega$ is equal to $2\pi f$, where $f$ is a frequency of excitation of the polyphase waveguide probe, $\varepsilon_o$ is a permittivity of free space, $\varepsilon_r$ is a relative permittivity of the lossy conducting medium, and a free-space wave number $k_o$ is equal to $\frac{2\pi}{\lambda_o}$, where $\lambda_o$ is a free-space wavelength of the polyphase waveguide probe, $j$ is equal to $\sqrt{-1}$, $\rho$ is a radial coordinate, $z$ is a vertical coordinate normal to the lossy conducting medium, $\varphi$ is an azimuthal coordinate, $I_o$ is a net polyphase probe current, and $H_1^{(2)}(-j\gamma\rho)$ is a Hankel function of a second kind and first order with complex argument $-j\gamma\rho$ for an $e^{+j\omega t}$ time variation, where $t$ is time.

109. The apparatus of any one of claims 3-98, wherein the Zenneck surface wave mode is substantially expressed as

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

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

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

where $H_\phi$ is an azimuthal magnetic field strength, $E_\rho$ is a radial electric field strength, $E_z$ is a vertical electric field strength, where γ is a surface wave radial propagation constant given by $\gamma = j\sqrt{k_o^2 + u_2^2}$ and $u_2$ is a vertical propagation constant given by $u_2 = \frac{-jk_o}{\sqrt{1 + (\varepsilon_r - jx)}}$, where $x \equiv \frac{\sigma}{\omega \varepsilon_o}$, $\sigma$ is a conductivity of the lossy conducting medium, ω is equal to $2\pi f$, where $f$ is a frequency of excitation of the polyphase waveguide probe, $\varepsilon_o$ is a permittivity of free space, $\varepsilon_r$ is a relative permittivity of the

conducting lossy medium, and a free-space wave number $k_o$ is equal to $\frac{2\pi}{\lambda_o}$, where $\lambda_o$ is a free-space wavelength of the polyphase waveguide probe, $j$ is equal to $\sqrt{-1}$, $\rho$ is a radial coordinate, $z$ is a vertical coordinate normal to the lossy conducting medium, $\varphi$ is an azimuthal coordinate, $I_o$ is a net polyphase probe current, $H_1^{(2)}(-j\gamma\rho)$ is a Hankel function of a second kind and first order with complex argument $-j\gamma\rho$, and $H_0^{(2)}(-j\gamma\rho)$ is a Hankel function of a second kind and zero order with complex argument $-j\gamma\rho$ for an $e^{+j\omega t}$ time variation, where $t$ is time.

~~11. An apparatus, comprising:~~

~~a polyphase waveguide probe configured to create a plurality of resultant fields; and~~

~~wherein the resultant fields are substantially mode-matched to a Zenneck surface wave mode on a surface of a terrestrial medium.~~

~~12. The apparatus of claim 11, wherein the resultant fields substantially synthesize a wave incident at a complex Brewster angle of the terrestrial medium, resulting in substantially zero reflection.~~

~~13~~10. The apparatus of any one of claim~~s 11 or 12~~ 3-7 or 8-9, wherein the excitation source is ~~polyphase waveguide probe further comprises a pair of charge terminals, the polyphase waveguide probe being further~~ configured to apply ~~impose~~ a plurality of voltage magnitudes and a plurality of phases on the plurality of charge terminals.

~~14~~11. The apparatus of claim ~~13~~10, wherein the polyphase waveguide probe further comprises a coil coupled between the charge terminals.

~~15~~12. A method, comprising ~~the step of~~:

positioning a receive circuit above a surface of ~~relative to~~ a terrestrial medium; and

receiving, via the receive circuit, energy transmitted from a polyphase waveguide probe ~~conveyed~~ in a form of a Zenneck surface wave along the ~~on a~~ surface of the terrestrial medium.

~~16~~13. The method of claim ~~15~~12, wherein an electrical load coupled to the receive circuit loads an excitation source coupled to ~~a~~ the polyphase waveguide probe that produces ~~generates~~ the Zenneck surface wave.

~~17~~14. The method of claim ~~15~~12, 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.

~~18~~15. The method of any one of claims ~~15~~12-~~17~~14, further comprising ~~the step of~~ impedance-matching an electrical load to the receive circuit.

~~19~~16. The method of any one of claims ~~16~~13-~~18~~15, further comprising ~~the step of~~ establishing a maximum power transfer from the receive circuit to the electrical load.

~~20~~17. An apparatus, comprising:

a receive circuit operable to receive ~~that receives~~ energy transmitted from a polyphase waveguide probe ~~conveyed~~ in a form of a Zenneck surface wave along a surface of a lossy conducting medium when the receive circuit is positioned above the lossy conducting medium.

~~21~~18. The apparatus of claim ~~20~~17, wherein the lossy conducting medium ~~further comprises~~ is or includes a terrestrial medium.

~~22~~19. The apparatus of any one of claims ~~20~~17 or ~~21~~18, wherein an electrical load coupled to the receive circuit loads an excitation source coupled to ~~a~~ the polyphase waveguide probe that generates the Zenneck surface wave.

~~23~~20. The apparatus of any one of claims ~~20~~17-~~22~~19, wherein the receive circuit ~~further~~ comprises one of a magnetic coil, a linear probe, or a tuned resonator.

~~24~~21. A power transmission system, comprising:

a polyphase waveguide probe formed of a plurality of charge terminals positioned relative to a ~~that transmits electrical energy in a form of a guided surface wave along a surface of a terrestrial~~ lossy conducting medium;

an excitation source coupled to the plurality of charge terminals, wherein the excitation source is operable to excite the plurality of charge terminals, the excitation of the plurality of charge terminals generating a plurality of electromagnetic fields which are substantially mode-matched to a Zenneck surface wave mode on a surface of the lossy conducting medium; and

a receive circuit operable to receive ~~that receives the~~ electrical energy from the polyphase waveguide probe via a guided surface wave along the surface of the lossy conducting medium.

2522. The power transmission system of claim 2421, wherein an electrical load coupled to the receive circuit loads the polyphase waveguide probe.

2623. The power transmission system of claim 2421, wherein an electrical load is coupled to the receive circuit and the electrical energy is used as a power source for the electrical load.

~~27~~24. The power transmission system of any one of claims ~~25~~-22 or ~~26~~23, wherein a maximum power transfer is established from the receive circuit to the electrical load.