SUMMARY

[0003] Aspects of the present disclosure are related to systems, methods and apparatus comprising anisotropic constitutive parameter (ACP) elements that can be used to launch or receive Zenneck surface waves (ZSWs), or other types of surface waves. In one aspect, among others, a guided surface wave apparatus comprises a launching transducer or a receiving transducer; and an array of anisotropic constitutive parameter (ACP) elements distributed above a terrestrial medium and about at least a portion of the launching structure or the receiving transducer, the array of ACP elements comprising: a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements positioned above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, wherein the first plurality of the RRAAD elements forms a horizontal layer at a height above the terrestrial medium. The array of ACP elements can be a cylindrical array with each of the one or more series of interconnected RRAAD elements linearly oriented in a ρ-direction.

[0004] The array of ACP elements can comprise a second horizontal layer of RRAAD elements positioned above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the height above the terrestrial medium. The second horizontal layer of RRAAD elements can comprise a second plurality of RRAAD elements positioned above the first plurality of RRAAD elements in the horizontal layer, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in the first orientation. The array of ACP elements can comprise a second plurality of RRAAD elements positioned above the terrestrial medium, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation, wherein the first plurality of the RRAAD elements and the second plurality of the RRAAD elements form the horizontal layer at the height above the terrestrial medium. RRAAD elements of the one or more series of interconnected RRAAD elements of the first plurality of RRAAD elements and the one or more series of interconnected RRAAD elements of the

second plurality of RRAAD elements can be separated from adjacent elements in that series by a defined distance. The array of ACP elements can be a rectangular array with the one or more series of interconnected RRAAD elements of the first plurality of RRAAD elements linearly oriented in an x-direction and the one or more series of interconnected RRAAD elements of the second plurality of RRAAD elements linearly oriented in a y-direction substantially perpendicular to the x-direction.

[0005] The launching structure can be configured to excite the array of ACP elements with an electromagnetic field at a frequency (f_0) thereby substantially mode matching the electromagnetic field to a Zenneck surface wave mode of the terrestrial medium. The receiving structure can be configured to couple with a Zenneck surface wave propagating along the terrestrial medium at a frequency (f_0) via the array of ACP elements, wherein the array of ACP elements is configured to concentrate electromagnetic energy from the Zenneck surface wave around the receiving structure. Individual RRAAD elements of the array of ACP elements can comprise a capacitor and a resistor connected in parallel, the capacitor and resistor comprising one or more lumped element components. The array of ACP elements can comprise a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed above the terrestrial medium, the plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer. The guided surface wave apparatus can comprise an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements distributed about the launching structure or the receiving structure, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

[0006] In another aspect, a method comprises providing a plurality of anisotropic constitutive parameter (ACP) elements about at least a portion of a launching transducer or a receiving transducer; and configuring the plurality of ACP elements in an array above a terrestrial medium,

wherein configuring the array of ACP elements comprises: positioning a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, the first plurality of the RRAAD elements forming a horizontal layer at a height above the terrestrial medium. The method can comprise exciting the array of ACP elements with an electromagnetic field produced by the launching structure, the array of ACP elements configured to substantially mode match the electromagnetic field at a frequency (f_0) to a Zenneck surface wave mode of the terrestrial medium; and coupling energy from the launching structure into a Zenneck surface wave propagating along the terrestrial medium via the array of ACP elements. The method can comprise concentrating, via the array of ACP elements, electromagnetic energy from a Zenneck surface wave propagating along the terrestrial medium at a frequency (f_0); extracting power from the concentrated electromagnetic energy from the Zenneck surface wave via the receiving structure; and providing at least a portion of the extracted power to a load.

[0007] The array of ACP elements can be a cylindrical array with each of the one or more series of interconnected RRAAD elements linearly oriented in a ρ-direction. Configuring the array of ACP elements can comprise positioning a second plurality of RRAAD elements in a second horizontal layer above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the height above the terrestrial medium. The second plurality of RRAAD elements can comprise one or more series of interconnected RRAAD elements extending in the first orientation. The second plurality of RRAAD elements can comprise one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation. The array of ACP elements can be a rectangular array with the one or more series of interconnected RRAAD elements of the first plurality of RRAAD elements linearly oriented in an x-direction and the

one or more series of interconnected RRAAD elements of the second plurality of RRAAD elements linearly oriented in a y-direction substantially perpendicular to the x-direction.

[0008] Configuring the array of ACP elements can comprise positioning a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed about the launching structure or the receiving structure, the plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer. The method can comprise configuring an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements about the launching structure or the receiving structure, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

[0009] In another aspect, a guided surface wave system comprises an array of anisotropic constitutive parameter (ACP) elements distributed above a terrestrial medium and about at least a portion of a launching transducer, the array of ACP elements comprising a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements positioned above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, wherein the first plurality of the RRAAD elements forms a horizontal layer at a height above the terrestrial medium, where excitation of the array of ACP elements with an electromagnetic field produced by the launching structure at a frequency (f_0) substantially mode matches the electromagnetic field to a Zenneck surface wave mode of the terrestrial medium; and a receiving transducer configured to extract power from electromagnetic energy from a Zenneck surface wave propagating along the terrestrial medium from the launching transducer. The guided surface wave system can comprise a second array of ACP elements distributed above the terrestrial medium about the receiving structure, the second array of ACP elements configured to configured to concentrate the electromagnetic energy from the Zenneck surface wave around the receiving structure, wherein the receiving structure

extracts power from the concentrated electromagnetic energy from the Zenneck surface wave.

[0010] The array of ACP elements can comprise a second horizontal layer of RRAAD elements positioned above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the height above the terrestrial medium, the second horizontal layer of RRAAD elements comprising a second plurality of RRAAD elements positioned above the first plurality of RRAAD elements in the horizontal layer. The array of ACP elements can comprise a second plurality of RRAAD elements positioned above the terrestrial medium, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation, wherein the first plurality of the RRAAD elements and the second plurality of the RRAAD elements form the horizontal layer at the height above the terrestrial medium. The array of ACP elements can comprise a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed above the terrestrial medium, the plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer. The guided surface wave system can comprise an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements distributed about the launching structure, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

[0011] Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims. In addition, all optional and preferred features and modifications of the described embodiments are usable in all aspects of the disclosure taught herein. Furthermore, the individual features of the dependent

Therefore, at least the following is claimed:

1. A guided surface wave apparatus, comprising:

a launching transducer or a receiving transducer; and

an array of anisotropic constitutive parameter (ACP) elements distributed above a terrestrial medium and about at least a portion of the launching transducer or the receiving transducer, the array of ACP elements comprising:

a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements positioned above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, wherein the first plurality of the RRAAD elements forms a horizontal layer at a height above the terrestrial medium.

2. The guided surface wave apparatus of claim 1, wherein the array of ACP elements is a cylindrical array with each of the one or more linear series of interconnected RRAAD elements linearly oriented in a ρ-direction.

3. The guided surface wave apparatus of claim 1, wherein the array of ACP elements comprises a second horizontal layer of RRAAD elements positioned above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the height above the terrestrial medium, the second horizontal layer of RRAAD elements comprising:

a second plurality of RRAAD elements positioned above the first plurality of RRAAD elements in the horizontal layer, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in the first orientation.

4. The guided surface wave apparatus of claim 1, wherein the array of ACP elements comprises a second plurality of RRAAD elements positioned above the terrestrial medium, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation, wherein the first plurality of the RRAAD elements and the second plurality of the RRAAD elements form the horizontal layer at the height above the terrestrial medium.

5. The guided surface wave apparatus of claim 4, wherein RRAAD elements of the one or more linear series of interconnected RRAAD elements of the first plurality of RRAAD elements and the one or more series of interconnected RRAAD elements of the second plurality of RRAAD elements are separated from adjacent elements in that series by a defined distance.

6. The guided surface wave apparatus of claim 4, wherein the array of ACP elements is a rectangular array with the one or more linear series of interconnected RRAAD elements of the first plurality of RRAAD elements linearly oriented in an x-direction and the one or more series of interconnected RRAAD elements of the second plurality of RRAAD elements linearly oriented in a y-direction substantially perpendicular to the x-direction.

7. The guided surface wave apparatus of claim 1, wherein the launching transducer is configured to excite the array of ACP elements with an electromagnetic field at a frequency (f_0) thereby substantially mode matching the electromagnetic field to a Zenneck surface wave mode of the terrestrial medium.

8. The guided surface wave apparatus of claim 1, wherein the receiving transducer is configured to couple with a Zenneck surface wave propagating along the terrestrial medium at a frequency (f_0) via the array of ACP elements, wherein the array of ACP elements is configured to concentrate electromagnetic energy from the Zenneck surface wave around the receiving transducer.

9. The guided surface wave apparatus of claim 1, wherein individual RRAAD elements of the array of ACP elements comprise a capacitor and a resistor connected in parallel, the capacitor and resistor comprising one or more lumped element components.

10. The guided surface wave apparatus of claim 1, wherein the array of ACP elements comprises a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed above the terrestrial medium, the plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer.

11. The guided surface wave apparatus of claim 1, comprising an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements distributed about the launching transducer or the receiving transducer, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

12. A method, comprising:

providing a plurality of anisotropic constitutive parameter (ACP) elements about at least a portion of a launching transducer or a receiving transducer; and

configuring the plurality of ACP elements in an array above a terrestrial medium, wherein configuring the array of ACP elements comprises:

positioning a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, the first plurality of the RRAAD elements forming a horizontal layer at a height above the terrestrial medium.

13. The method of claim 12, further comprising:

exciting the array of ACP elements with an electromagnetic field produced by the launching transducer, the array of ACP elements configured to substantially mode match the electromagnetic field at a frequency (f_0) to a Zenneck surface wave mode of the terrestrial medium; and

coupling energy from the launching transducer into a Zenneck surface wave propagating along the terrestrial medium via the array of ACP elements.

14. The method of claim 12, further comprising:

concentrating, via the array of ACP elements, electromagnetic energy from a Zenneck surface wave propagating along the terrestrial medium at a frequency (f_0);

extracting power from the concentrated electromagnetic energy from the Zenneck surface wave via the receiving transducer; and

providing at least a portion of the extracted power to a load.

15. The method of claim 12, wherein the array of ACP elements is a cylindrical array with each of the one or more linear series of interconnected RRAAD elements linearly oriented in a ρ-direction.

16. The method of claim 12, wherein configuring the array of ACP elements comprises positioning a second plurality of RRAAD elements in a second horizontal layer above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the height above the terrestrial medium.

17. The method of claim 16, wherein the second plurality of RRAAD elements comprise one or more series of interconnected RRAAD elements extending in the first orientation.

18. The method of claim 16, wherein the second plurality of RRAAD elements comprise one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation.

19. The method of claim 12, wherein the array of ACP elements is a rectangular array with the one or more linear series of interconnected RRAAD elements of the first plurality of RRAAD elements linearly oriented in an x-direction and the one or more series of interconnected RRAAD elements of the second plurality of RRAAD elements linearly oriented in a y-direction substantially perpendicular to the x-direction.

20. The method of claim 12, wherein configuring the array of ACP elements comprises positioning a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed about the launching transducer or the receiving transducer, the

plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer.

21. The method of claim 12, can comprise configuring an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements about the launching transducer or the receiving transducer, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

22. A guided surface wave system, comprising:

an array of anisotropic constitutive parameter (ACP) elements distributed above a terrestrial medium and about at least a portion of a launching transducer, the array of ACP elements comprising a first plurality of radial resistive artificial anisotropic dielectric (RRAAD) elements positioned above the terrestrial medium, the first plurality of RRAAD elements comprising one or more linear series of interconnected RRAAD elements extending in a first orientation, wherein the first plurality of the RRAAD elements forms a horizontal layer at a height above the terrestrial medium, where excitation of the array of ACP elements with an electromagnetic field produced by the launching transducer at a frequency (f_0) substantially mode matches the electromagnetic field to a Zenneck surface wave mode of the terrestrial medium; and

a receiving transducer configured to extract power from electromagnetic energy from a Zenneck surface wave propagating along the terrestrial medium from the launching transducer.

23. The guided surface wave system of claim 22, wherein the array of ACP elements comprises a second horizontal layer of RRAAD elements positioned above, and substantially parallel to, the horizontal layer of RRAAD elements distributed at the

height above the terrestrial medium, the second horizontal layer of RRAAD elements comprising a second plurality of RRAAD elements positioned above the first plurality of RRAAD elements in the horizontal layer.

24. The guided surface wave system of claim 22, wherein the array of ACP elements comprises a second plurality of RRAAD elements positioned above the terrestrial medium, the second plurality of RRAAD elements comprising one or more series of interconnected RRAAD elements extending in a second orientation with respect to the first orientation, wherein the first plurality of the RRAAD elements and the second plurality of the RRAAD elements form the horizontal layer at the height above the terrestrial medium.

25. The guided surface wave system of claim 22, wherein the array of ACP elements comprises a plurality of vertical lossless artificial anisotropic dielectric (VLAAD) elements distributed above the terrestrial medium, the plurality of VLAAD elements positioned above the terrestrial medium, the plurality of VLAAD elements comprising one or more series of interconnected VLAAD elements extending in a second orientation substantially perpendicular to the horizontal layer.

26. The guided surface wave system of claim 22, comprising an array of horizontal artificial anisotropic magnetic permeability (HAAMP) elements distributed about the launching transducer, the array of HAAMP elements comprising a plurality of HAAMP elements positioned above the terrestrial medium.

27. The guided surface wave system of claim 22, comprising a second array of ACP elements distributed above the terrestrial medium about the receiving transducer, the second array of ACP elements configured to configured to concentrate the electromagnetic energy from the Zenneck surface wave around the receiving

transducer, wherein the receiving transducer extracts power from the concentrated electromagnetic energy from the Zenneck surface wave.