Abstract: A dual-polarization, circularly-polarized artificial-impedance-surface antenna has two adjacent tensor surface-wave waveguides (SWGs), a waveguide feed coupled to each of the two SWGs and a hybrid coupler having output ports, each output port of the hybrid coupler being connected to the waveguide feeds coupled to the two SWGs, the hybrid coupler, in use, combining the signals from input ports of the 90 hybrid coupler with phase shifts at its output ports.
Dual-polarization, circularly-polarized, surface-wave-waveguide, artificial-impedance-surface antenna

Cross Reference to Related Applications

[0001] This application is related to US Patent Application Serial No. 13/744,295 filed 01/17/2013 and entitled "Surface Wave Guiding Apparatus and Method", the disclosure of which is incorporated herein by reference. This application claims priority to and claims the benefit of U.S. Application Serial No. 14/310,895 filed June 20, 2014, which is hereby incorporated by reference in its entirety.

Statement Regarding Federally Sponsored Research or Development

[0002] None.

Technical Field

[0003] This invention provides an antenna capable of dual-polarization, circularly-polarized simultaneous Right Hand Circular Polarization (RHCP) and Left Hand Circular Polarization (LHCP) operation.

Background

[0004] Linearly-polarized AIS Antennas

[0005] Artificial impedance surface antennas (AISAs) are realized by launching a surface wave across an artificial impedance surface (AIS), whose impedance is spatially modulated across the AIS according a function that matches the phase fronts between the surface wave on the AIS and the desired far-field radiation pattern.

[0006] In the prior art, an artificial impedance surface antenna (AISA) is formed from modulated artificial impedance surfaces (AIS). The prior art, in this regard, includes:


[0009] The basic principle of AISA operation is to use the grid momentum of the modulated AIS to match the wavevector of an excited surface-wave front to a desired plane wave. In the one-dimensional case, this can be expressed as

\[ k_{sw} = k_r \sin \theta - k_s, \]  

(Eqn. 1)

where \( k_r \) is the radiation's free-space wavenumber at the design frequency, \( \theta \) is the angle of the desired radiation with respect to the AIS normal, \( k_p \cdot 2np \) is the AIS grid momentum where \( p \) is the AIS modulation period, and \( k_{sw} = n, k_r \) is the surface wave's wavenumber, where \( n_0 \) is the surface wave's refractive index averaged over the AIS modulation. The Surface Wave (SW)
impedance is typically chosen to have a pattern that modulates the SW impedance sinusoidally along the Surface Wave Guide (SWG) according to the following equation:

\[ Z(x) = X + M \cos(2\pi x / p) \]  

(Eqn. 2)

where \( p \) is the period of the modulation, \( X \) is the mean impedance, and \( M \) is the modulation amplitude. \( X, M \) and \( p \) are chosen such that the angle of the radiation \( \Theta \) in the x-z plane w.r.t the z axis is determined by

\[ \Theta = \sin^{-1} \left( \frac{\omega_0 - \lambda_0}{p} \right) \]  

(Eqn. 3)

where \( \omega_0 \) is the mean SW index and \( \lambda_0 \) is the free-space wavelength of radiation, \( \omega_0 \) is related to \( Z(x) \) by

\[ n_0 = \frac{1}{p} \int_0^p \sqrt{1 + Z(x)^2} \, dx = \sqrt{1 + X^2} \] .

The AISA impedance modulation of Eqn. 2 can be generalized for an AISA of any shape as

\[ Z(\vec{r}) = X + M \cos(k_o n_o r - \vec{k}_o \cdot \vec{r}) \]

where \( \vec{k}_o \) is the desired radiation wave vector, \( \vec{r} \) is the three-dimensional position vector of the AIS, and \( r \) is the distance along the AIS from the surface-wave source to \( \vec{r} \) along a geodesic on the AIS surface. This expression can be used to determine the index modulation for an AISA of any geometry, flat, cylindrical, spherical, or any arbitrary shape. In some cases, determining the value of \( r \) is geometrically complex. For a flat AISA, it is simply \( r = \sqrt{x^2 + y^2} \).

For a flat AISA designed to radiate into the wavevector at \( \vec{k}_o = k_o (\sin \theta_o \hat{x} + \cos \theta_o \hat{z}) \), with the surface-wave source located at \( x-y-0 \), the modulation function is

\[ Z(x, y) = X + M \cos \gamma \]

where \( \gamma = k_o (\omega_0 r - x \sin \theta_o) \) .

(Eqn. 4)
The \( \cos \) function in Eqn. 2 and Eqn. 3 can be replaced with any periodic function and the AISA will still operate as designed, but the details of the side lobes, bandwidth and beam squint will be affected.

The AISA can be realized as a grid of metallic patches disposed on a grounded dielectric that produces the desired index modulation by varying the size of the patches according to a function that correlates the patch size to the surface wave index. The correlation between index and patch size can be determined using simulations, calculation and/or measurement techniques. For example, Colburn and Fong (see references cited above) use a combination of HFSS unit-cell eigenvalue simulations and near-field measurements of test boards to determine their correlation function. Fast approximate methods presented by Luukkonen (see, for example, O. Luukkonen et al., "Simple and accurate analytical model of planar grids and high-impedance surfaces comprising metal strips or patches", IEEE Trans. Antennas Prop., vol. 56, 1624, 2008) can also be used to calculate the correlation. However, empirical correction factors are often applied to these methods. In many regimes, these methods agree very well with HFSS eigenvalue simulations and near-field measurements. They break down when the patch size is large compared to the substrate thickness, or when the surface-wave phase shift per unit cell approaches 180°.

### Circularly-polarized AIS Antennas

An AIS antenna can be made to operate with circularly-polarized (CP) radiation by using an impedance surface whose impedance properties are anisotropic. Mathematically, the impedance is described at every point on the AIS by a tensor. In a generalization of the modulation function of equation (3) for the linear-polarized AISA [4], the impedance tensor of the CP AISA may have a form like

\[
Z = \begin{bmatrix}
X - \frac{1}{2} M \sin(\gamma - \phi) & \frac{1}{2} M \sin(\gamma - \phi) \\
\frac{1}{2} M \sin(\gamma - \phi) & X + M \sin(\gamma - \phi)
\end{bmatrix},
\]

(Eqn. 5)

where \( \tan \phi \equiv \frac{Y}{X} \).

(Eqn. 6)
In the article by B. Fong et al. identified above, the tensor impedance is realized with anisotropic metallic patches on a grounded dielectric substrate. The patches are squares of various sizes with a slice through the center of them. By varying the size of the patches and the angle of the slice through them, the desired tensor impedance of equation Eqn. 5 can be created across the entire AIS. Other types of tensor impedance elements besides the "sliced patch" can be used to create the tensor AIS.

Surface-wave waveguide AIS antennas

A variation on the AIS antennas utilizes surface-wave waveguides to confine the surface waves along narrow paths that form one-dimensional ES AISAs. Surface-wave waveguides (SWG) are surface structures that constrain surface-waves (SW) to propagate along a confined path (see, for example, D. J. Gregoire and A. V. Kabakian, "Surface-Wave Waveguides," Antennas and Wireless Propagation Letters, IEEE, 10, 2011, pp. 1512-1515). In the simplest SWG, the structure interacts with surface waves in the same way that a fiber-optic transmission line interacts with light. The physical principle is the same: the wave preferentially propagates in a region of high refractive index surrounded by a region of low refractive index. In the case of the fiber optic, or any dielectric waveguide, the high- and low-index regions are realized with high and low-permittivity materials. In the case of the SWG, the high- and low-index regions can be realized with metallic patches of varying size and/or shape on a dielectric substrate.

The surface-wave fields across the width of the SWG are fairly uniform when the width of the SWG is less than approximately ¾ surface-wave wavelength. So, this is a good rule of thumb for the SWG.

In a linearly-polarized SWG AISA, the impedance of the SWG varies according to equation Eqn. 2. The impedance elements can be square patches of metal on the substrate or they can be strips that span the width of the SWG. The desired impedance modulation is created by varying the size of the impedance element dimensions with position.
[0019] In a circularly-polarized SWG, the tensor impedance varies according to equation Eqn. 5 with \( \phi = 0 \). The impedance elements can be the sliced patches as described by B. Fong et al. (see the B. Fong et al. article referenced above). The impedance element dimensions are varied with position to achieve the desired impedance variation.

**Brief description of the Invention**

[0020] In one aspect the present invention provides a dual-polarization, circularly-polarized artificial-impedance-surface antenna comprising: (1) two adjacent tensor surface-wave waveguides (SWGs); (2) a waveguide feed coupled to each of the two SWGs; (3) a hybrid coupler (which is preferably a 90° coupler) having output ports, each output port of the hybrid coupler being connected to the waveguide feeds coupled to the two SWGs, the hybrid coupler, in use, combining the signals from input ports of the hybrid coupler with phase shifts at its output ports.

[0021] In another aspect the present invention provides a method of simultaneously transmitting two oppositely handed circularly polarized RF signals comprising the steps of: (i) providing a dielectric surface with a ground plane on one side there of and with a pair of elongate artificial impedance surface antennas, each of said artificial impedance surface antennas including a pattern of metallic geometric stripes or shapes disposed on said dielectric surface, the metallic geometric stripes or shapes having varying sizes which form a repeating moire pattern, the moire patterns of the each of said pair of elongate artificial impedance surface antennas having a angular relationship with reference to a major axis of said pair of elongate artificial impedance surface antennas, a first one of said pair of elongate artificial impedance surface antennas having a positive angular relationship to said major axis and second one of said pair of elongate artificial impedance surface antennas having a negative angular relationship to said major axis; and (ii) applying RF energy to said pair of elongate artificial impedance surface antennas, said RF energy applied to said pair of elongate artificial impedance surface antennas having different relative phases selected such that RF signals transmitted by said pair of elongate artificial impedance surface antennas is circularly polarized.
[0022] In yet another aspect the present invention provides a method of simultaneously receiving two oppositely handed circularly polarized RF signals comprising the steps of: (i) sending the signals received by two SWGs into two input ports of a 3dB 90 degree hybrid coupler, the coupler also having two output ports; and (ii) extracting LHCP and RHCP signals from the output two ports of the hybrid coupler.

**Brief Description of the Drawings**

[0023] Fig. 1a is top view of one embodiment of the present invention disposed on a printed circuit board while Fig. 1b is a side elevational view thereof.

[0024] Fig. 2 is a schematic view of another embodiment of a SWG which may be used with the present invention.

[0025] Fig. 3 is a schematic view of yet another embodiment of a SWG which may be used with the present invention.

**Detailed Description**

[0026] This invention provides a solution for a dual-polarization, circularly-polarized AISA with simultaneous Right Hand Circular Polarization (RHCP) and Left Hand Circular Polarization (LHCP) operation.

[0027] Referring to Figs. 1a and 1b, one possible embodiment of the invention includes a pair of linearly-polarized SWGs 101 and 102 to form the AISA. The polarization of the two SWGs 101-, 102 is preferably rotated by 90° with respect to each other. The SWGs 101, 102 are connected to ports C and D of a 3-dB 90° hybrid coupler 103, the operation of which is well understood in the state of the art (see, for example, www.microwaves101.com/encyclopedia/hybridcouplers.cfm). The signals at ports C and D are the sum of the signals at ports A and B with preferably either a 90° or a -90° phase shift between them, respectively. The combination of the radiation from the two SWGs 101, 102 with the 90° rotation in polarization and the 90°
separation in phase results in circularly polarized radiation. It is well known that circularly polarized radiation can be created by combining radiation from two antennas with orthogonal polarization with a 90° phase shift between them. The signal connected to port A is transmitted or received with RHCP polarization while the signal connected to port B simultaneously is transmitted or received with LHCP polarization. Transmit-Receive (TR) switches 104 enable independent operation of each polarization in transmit or receive modes depending on the positions of switches 104. The two channels are processed in receive mode by conventional front-end electronics 105 and the two channels are provided in transmit mode with transmit signals again by conventional front-end electronics 105. The conventional front-end electronics 105 may be embodied in or by a transceiver with dual inputs (R1 and R2) and dual outputs (T1 and T2) or in or by separate transmitters and receivers or in or by a RF transmit/receive module.

[0028] Each of the SWGs 101, 102 is a linear array of tensor impedance elements 106 that radiate with a polarization preferably at a ±45° angle to the polarization of the SW electric field (in the x axis labeled in Fig. 1, the x axis also being the major axis or axis of common elongation of the two SWGs 101, 102). The tensor elements 106 are preferably metallic shapes printed or otherwise formed on the top surface of a dielectric substrate 109 which preferably has a ground plane 111 disposed the opposing (underside) surface of the dielectric substrate 109. The metallic shapes can be stripes as shown in Figs. 1a and 2, or they can be slit squares as shown in Fig. 3. Other electrically conductive shapes can alternatively be utilized as the tensor impedance elements 106 if desired. A ground potential associated with front-end electronics 105 is coupled with the ground plane 111 on bottom side of the dielectric substrate 109. The SWGs 101, 102 should preferably be spaced apart a sufficient distance so that the fields adjacent the SWGs do not couple with each other. In practice the separation distance between SWGs 101, 102 is preferably at least ¼ λ.

[0029] The tensor impedance elements 106 can be provided by metallic stripes disposed on a top side of the dielectric substrate 109 where the tensor impedance elements 106 in one channel are angled preferably at +45° with respect to the x axis, and the tilt angle of the stripes in the other channel is set to -45° with respect to that same axis. This variation in tilt angle produces
radiation of different linear polarization, that when combined with a 90° phase shift via the 90° hybrid 103, produces circularly polarized radiation in transmit mode or allow reception of circularly polarized radiation in receive mode. The impedance elements could also be square patches with slices through them as described in B. Fong et al; "Scalar and Tensor Holographic Artificial Impedance Surfaces", noted above. Such an embodiment is depicted by Fig. 3.

[0030] The dielectric substrate 109 may preferably be made from Printed Circuit Board (PCB) material which has a metallic conductor (such as copper) disposed preferably on both of its major surfaces, the metallic conductor on the top or upper surface being patterned using conventional PCB fabrication techniques to define the aforementioned tensor impedance elements 106 from the metallic conductor originally formed on the upper surface of the PCB. The metallic conductor formed on the lower surface of the PCB would then become the ground plane.

[0031] In transmit operation, the front-end electronics 105 sends two independent signals from its transmit channels (T1 and T2) to the transmit connections of the two TR switches 104. The TR switches 104 send the two transmit signals to ports A and B of the 90° hybrid coupler 103. If the voltages at ports A and B are \( V_A \) and \( V_B \), then the voltages \( V_c \) and \( V_D \) at ports C and D are \( (iV_A + V_B) / \sqrt{2} \) and \( (V_A + iV_B) / \sqrt{2} \), respectively where \( i = \sqrt{-1} \) and represents a 90° phase shift.

[0032] The signals from ports C and D of the 90° hybrid coupler 103 pass through optional coaxial cables 110 to end launch Printed Circuit Board (PCB) connectors 107 which are connected to surface-wave (SW) feeds 108. The coaxial cables 110 and connectors 107 may be omitted if coupler 103 is connected directly the SW feeds 108, for example. If coaxial cables 110 are utilized, then their respective center conductors are connected to the SW feeds 108 while their shielding conductor are connected to the ground plane 111. Instead of using coaxial cables 110 to connect outputs of the coupler 103 to the feeds 108, a link between the two can alternatively be provided by rectangular waveguides, microstrips, coplanar waveguides (CPWs), etc. The SW feeds 108 preferably have a 50 Ω impedance at the end that connects to coupler 103.
via the end-launch connector 107 (if utilized). The SW feed 108 flares from one end, preferably in an exponential curve, until its width matches the width of the SWGs 101, 102. The SW feeds 108 launch surface waves with a uniform field across their wide ends into the SWGs 101, 102. The SW feeds 108 are preferably formed using the same techniques to form the tensor impedance elements 106 (this is, by forming them from the metallic conductor found on a typical PCB). The widths of the SWGs 101, 102 is preferably between 1/8 to 2 wavelengths of an operational frequency (or frequencies) of the SWGs 102, 102.

[0033] The SWGs 101, 102 are preferably composed of a series of metallic tensor impedance elements 106 whose sides are preferably angled at 45° or having angled slices as in the embodiment of Fig. 3 with respect to the SWG axis (the x-axis in Fig. 1) as noted above. The slices are angled at ±45° with respect to the major axis of the SWGs 101, 102 axis so that the impedance tensor's principal axis is aligned with the slice. It should be noted that series of metallic tensor impedance elements 106 with angled slices or sides could be angled at some other angle than ±45° with respect to the SWG axis (the x-axis in Fig. 1), but in that case the hybrid coupler 103 has to have a phase shift that is different from 90 degrees at its outputs. Such a hybrid coupler 103 is not believed to be commercially available, so it would be a custom designed coupler, but such a coupler could be designed and made if desired. So the angles of ±45° with respect to the SWG axis (the x-axis in Fig. 1) set for the angles of the metallic tensor impedance elements 106 (or the angles of the slices or sides of the as in the embodiment of Fig. 3) is preferred as those angles are believed to be compatible with commercially available hybrid couplers for elements 103.

[0034] The widths of the individual metallic tensor impedance elements 106 are typically much narrower than the widths of the SWGs 101, 102 which they form. In Fig. 1 the widths of the individual metallic tensor impedance elements 106 averages about 1/7th of the width of the SWGs 101, 102. Typically, the individual metallic tensor impedance elements 106 will be spaced by 1/20 to 1/5 of a wavelength apart from each other along the length of the SWGs 101, 102. The width of the individual metallic tensor impedance elements 106 determines the SW propagation impedance locally along the SWG. The width of the tensor impedance elements 106 varies with
distance along the SWG such that the SW impedance is modulated according to equation (Eqn. 2), in order to have the radiation pattern directed at an angle \( \theta \) determined by equation (Eqn. 3) with respect to the z axis in the x-z plane noted on Fig. 1. This variation in the widths of the tensor impedance elements 106 can be seen in Fig. 1 as a noticeable moire pattern caused by the changing widths of the tensor impedance elements 106. This pattern repeats itself continuously along the length of the SWG, no matter how long the SWG is. The length of the SWG 101, 102 will depend on a number of factors related to the antenna's engineering parameters, such as desired radiation beam width, gain, instantaneous bandwidth, aperture efficiency, etc. Typically the length of the SWGs 101, 102 will fall in the range of 2 to 30 wavelengths at the operational frequency of the SWGs 101, 102.

[0035] The relation between the impedance-element geometry (e.g. the strip width) and the SW impedance is well understood. See the papers by Patel, Sievenpiper, Colburn, Fong and Gregoire identified above.

[0036] The metallic tensor impedance elements 106 in SWG 101 are angled in a direction opposite to the tensor impedance elements 106 in the other SWG 102. The radiation from the two SWGs will be polarized in the direction across the gaps between the strips. Therefore, the radiation from the two SWGs 101, 102 depicted by Fig. 1 will be orthogonal to each other. When the 90° phase shift difference is applied to the feeds 108 with the hybrid power splitter 103, the net radiation from the combination of the two SWGs 101, 102 is circularly polarized. However, as noted above other angles (then 45°) for the metallic tensor impedance elements 106 relative to the x-axis can be utilized if a custom designed coupler 103 is employed and still the resulting polarization will be polar.

[0037] The radiation from each SWG 101, 102 is polarized as it is because the slanted metallic strips are tensor impedance elements 106 whose major principal axis is perpendicular to the long edge of the strips and the minor axis is along them. The local tensor admittance of the SWG in the coordinate frame of the principal axes is
\[ Y(x) = \begin{bmatrix} Y(x) & 0 \\ 0 & 0 \end{bmatrix} \]

where \( Y(x) \) is determined by the voltage applied to the metallic strips at position \( x \). Then the SW current is

\[ \mathbf{J}_{SW} = Y_{SW} \mathbf{E}_{SW} = \begin{bmatrix} Y(x) & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_{SW} \end{bmatrix} \mathbf{k} / \sqrt{2} = E_{SW} / \sqrt{2} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \]

which is along the major principal axis that is perpendicular to the long edge of the strips forming the tensor impedance elements 106. The radiation is driven by the SW currents according to

\[ \mathbf{E}_{rad} \propto \int \left[ \mathbf{k} \times \mathbf{J}_{SW} \right] e^{-i \mathbf{k} \cdot \mathbf{r}} d\mathbf{x} e^{i \mathbf{k} \cdot \mathbf{r}} \]

and is therefore polarized in the direction across the gaps between the strips.

[0038] The preferred embodiment for a 12 GHz version of a radiating element of the invention is shown in Fig. 1. Everything is scaled to a free-space wavelength at 12 GHz is \( \lambda_0 = 2.5 \text{ cm} = 1.0'' \). The SWGs 101 and 102 are preferably \( \frac{1}{2} \lambda_0 \) wide. The exponentially-tapered, surface-wave feeds 108 are preferably \( 2 \lambda_0 \) long. The period of the tensor impedance elements \( 106 = \frac{1}{12} \lambda_0 \).

[0039] Fig. 2 illustrates a preferred embodiment where an RF feed assembly 108 is also disposed at the other of the SWGs with RF terminators 201 attached to the end. This prevents the surface-wave from reflecting off the end of the AISA which could lead to unwanted distortion in the radiation pattern.

[0040] This concludes the description of embodiments of the present invention. It should now be apparent that the present invention relates to the following features and concepts:
[0041] Concept 1: A dual-polarization, circularly-polarized artificial-impedance-surface antenna comprising: two adjacent tensor surface-wave waveguides (SWGs); a waveguide feed coupled to each of the two SWGs; and a hybrid coupler having output ports, each output port of the hybrid coupler being connected to the waveguide feeds coupled to the two SWGs, the hybrid coupler, in use, combining the signals from input ports of the 90° hybrid coupler with phase shifts at its output ports.

[0042] Concept 2: The antenna of concept 1 wherein the SWGs metallic tensor impedance elements disposed on a common substrate.

[0043] Concept 3: The antenna of concepts 1 and/or 2 wherein the tensor impedance elements on the adjacent SWGs have principal axes of their impedance tensors rotated 90° with respect to each other and wherein the hybrid coupler is a 90° hybrid coupler.

[0044] Concept 4: The antenna of any one or more of the concepts 1-3 wherein the SWGs include metallic strips or patches disposed in an elongated array on a top surface of a dielectric sheet, the dielectric sheet having a ground plane on a bottom surface thereof.

[0045] Concept 5: The antenna of any one or more of the concepts 1-4 wherein the SWGs are elongated and each have a width which is between 1/8 to 2 wavelengths of an operational frequency of the SWGs and have a length which is between 2 and 30 wavelengths of said operational frequency of the SWGs.

[0046] Concept 6: The antenna of any one or more of the concepts 1-5 wherein each of the SWGs comprises metallic strips slanted at an angle with respect a common direction of elongation of the SWGs.

[0047] Concept 7: The antenna of concept 6 wherein said metallic strips are disposed at 45° angle with respect to said common direction of elongation of the SWGs.
Concept 8: The antenna of concept 7 wherein said metallic strips in one SWG are disposed at 90° angle with respect said metallic strips in the other SWG.

Concept 9: The antenna of concept 8 wherein said metallic strips are distributed along a length of each SWG.

Concept 10: The antenna of any one or more of the concepts 1-9 wherein the SWGs include impedance elements that are spaced with a period of 1/20 to 1/5 wavelength apart from each other along the length of the SWG.

Concept 11: The antenna of any one or more of the concepts 1-10 wherein the SWGs include impedance elements that are configured by their shape to produce a modulated impedance pattern according to

\[
Z(x) = X + M \cos(2\pi x / \rho)
\]

where \(\rho\) is the period of the modulation, \(X\) is the mean impedance, and \(M\) is the modulation amplitude. \(X, M\) and \(\rho\) can be tuned such that the angle of the radiation \(\Theta\) in the x-z plane with respect to the z axis is scanned according to

\[
\Theta = \sin^{-1}(\tfrac{\lambda_0}{\lambda} / \rho)
\]

where \(n_0\) is the mean SW index, and \(\lambda_0\) is the free-space wavelength of radiation and \(n_0\) is related to \(Z(x)\) by

\[
n_0 = \frac{1}{\rho} \int_0^\rho \sqrt{1 + Z(x)^2} \, dx \approx \sqrt{1 + \lambda^2}.
\]

Concept 12: The antenna of any one or more of the concepts 1-11 wherein the SWGs include impedance elements that are formed by patches with slices through them and wherein said slices are angled at 45° with respect to a major axis of the SWGs so as to form an impedance tensor having an impedance tensor principal axis which is aligned with said slices.
Concept 13: A method of simultaneously transmitting two oppositely handed circularly polarized RF signals comprising the steps of:

- providing a dielectric surface with a ground plane on one side there of and with a pair of elongate artificial impedance surface antennas, each of said artificial impedance surface antennas including a pattern of metallic geometric stripes or shapes disposed on said dielectric surface, the metallic geometric stripes or shapes having varying sizes which form a repeating moire pattern, the moire patterns of the each of said pair of elongate artificial impedance surface antennas having a angular relationship with reference to a major axis of said pair of elongate artificial impedance surface antennas, a first one of said pair of elongate artificial impedance surface antennas having a positive angular relationship to said major axis and second one of said pair of elongate artificial impedance surface antennas having a negative angular relationship to said major axis; and

- applying RF energy to said pair of elongate artificial impedance surface antennas, said RF energy applied to said pair of elongate artificial impedance surface antennas having different relative phases selected such that RF signals transmitted by said pair of elongate artificial impedance surface antennas is circularly polarized.

Concept 14: The method of concept 13 wherein the repeating moire pattern of the pair of elongate artificial impedance surface antennas has a 45 degree angular relationship with reference to the major axis, one of the repeating moire patterns having a positive 45 degree angular relationship with reference to the major axis and the other one of the repeating moire patterns having a negative 45 degree angular relationship with reference to the major axis and wherein the phase of RF energy applied to said pair of elongate artificial impedance surface antennas has a relative 90° phase difference.

Concept 15: A method of simultaneously receiving two oppositely handed circularly polarized RF signals comprising the steps of: sending the signals received by two SWGs into two
input ports of a coupler, the coupler also having two output ports; and extracting LHCP and RHCP signals from the output two ports of the hybrid coupler.

[0056] Concept 16: The method of concept 15 wherein the coupler is a 3dB 90 degree hybrid coupler.

[0057] The foregoing description of the disclosed embodiments and the methods of making same has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form or methods disclosed. Many modifications and variations are possible in light of the above teachings. It is intended that the scope of the invention be limited not by this detailed description or the concepts set forth above, but rather by the claims appended hereto.

[0058] All elements, parts and steps described herein are preferably included. It is to be understood that any of these elements, parts and steps may be replaced by other elements, parts and steps or deleted altogether as will be obvious to those skilled in the art.

[0059] Broadly, this writing discloses at least the following: A dual-polarization, circularly-polarized artificial-impedance-surface antenna has two adjacent tensor surface-wave waveguides (SWGs), a waveguide feed coupled to each of the two SWGs and a hybrid coupler having output ports, each output port of the hybrid coupler being connected to the waveguide feeds coupled to the two SWGs, the hybrid coupler, in use, combining the signals from input ports of the 90° hybrid coupler with phase shifts at its output ports.
What is claimed is:

1. A dual-polarization, circularly-polarized artificial-impedance-surface antenna comprising:
   (1) two adjacent tensor surface-wave waveguides (SWGs);
   (2) a waveguide feed coupled to each of the two SWGs; and
   (3) a hybrid coupler having output ports, each output port of the hybrid coupler being
   connected to the waveguide feeds coupled to the two SWGs, the hybrid coupler, in use,
   combining the signals from input ports of the 90° hybrid coupler with phase shifts at its output
   ports.

2. The antenna of claim 1 wherein the SWGs are disposed on a common substrate.

3. The antenna of claim 1 or 2 wherein tensor impedance elements on adjacently disposed SWGs
   have principal axes of their impedance tensors rotated 90° with respect to each other and
   wherein the hybrid coupler is a 90° hybrid coupler.

4. The antenna of any one of the preceding claims wherein the SWGs include metallic strips or
   patches disposed in an elongated array on a top surface of a dielectric sheet, the dielectric
   sheet having a ground plane on a bottom surface thereof.

5. The antenna of any one of claims 1 through 3 wherein the SWGs are elongated and each
   have a width which is between 1/8 to 2 wavelengths of an operational frequency of the SWGs
   and have a length which is between 2 and 30 wavelengths of said operational frequency of the
   SWGs.
6. The antenna of any one of claims 1 through 3 wherein each of the SWGs has metallic strips slanted at an angle with respect a common direction of elongation of the SWGs.

7. The antenna of claim 6 wherein said metallic strips are disposed at 45° angle with respect to said common direction of elongation of the SWGs.

8. The antenna of claim 7 wherein said metallic strips in one SWG are disposed at 90° angle with respect said metallic strips in the other SWG.

9. The antenna of claim 8 wherein said metallic strips are distributed along a length of each SWG.

10. The antenna of any one of claims 1 through 3 wherein the SWGs include impedance elements that are spaced with a period of 1/20 to 1/5 wavelength apart from each other along the length of the SWG.

11. The antenna of any one of claims 1 through 3 wherein the SWGs include impedance elements that are configured by their shape to produce a modulated impedance pattern according to

\[ Z(x) = X + M \cos(2\pi x/p) \]

where \( p \) is the period of the modulation, \( X \) is the mean impedance, and \( M \) is the modulation amplitude. \( X, M \) and \( p \) can be tuned such that the angle of the radiation \( \Theta \) in the x-z plane with respect to the z axis is scanned according to

\[ \Theta = \sin^{-1}\left(\frac{\Omega - \lambda_0}{p}\right) \]
where \( n_0 \) is the mean SW index, and \( \lambda_0 \) is the free-space wavelength of radiation and \( n_0 \) is related to \( Z(x) \) by

\[
n_0 = \frac{1}{p} \int_0^p \sqrt{1 + Z(x)^2} \, dx = \sqrt{1 + \chi^2}.
\]

12. The antenna of any one of the preceding claims wherein the SWGs include impedance elements that are formed by patches with slices through them and wherein said slices are angled at 45° with respect to a major axis of the SWGs so as to form an impedance tensor having an impedance tensor principal axis which is aligned with said slices.

13. A method of simultaneously transmitting two oppositely handed circularly polarized RF signals comprising the steps of:

- providing a dielectric surface with a ground plane on one side there of and with a pair of elongate artificial impedance surface antennas, each of said artificial impedance surface antennas including a pattern of metallic geometric stripes or shapes disposed on said dielectric surface, the metallic geometric stripes or shapes having varying sizes which form a repeating moire pattern, the moire patterns of the each of said pair of elongate artificial impedance surface antennas having a angular relationship with reference to a major axis of said pair of elongate artificial impedance surface antennas, a first one of said pair of elongate artificial impedance surface antennas having a positive angular relationship to said major axis and second one of said pair of elongate artificial impedance surface antennas having a negative angular relationship to said major axis; and
- applying RF energy to said pair of elongate artificial impedance surface antennas, said RF energy applied to said pair of elongate artificial impedance surface antennas having different relative phases selected such that RF signals transmitted by said pair of elongate artificial impedance surface antennas is circularly polarized.
14. The method of claim 13 wherein the repeating moire pattern of the pair of elongate artificial impedance surface antennas has a 45 degree angular relationship with reference to the major axis, one of the repeating moire patterns having a positive 45 degree angular relationship with reference to the major axis and the other one of the repeating moire patterns having a negative 45 degree angular relationship with reference to the major axis and wherein the phase of RF energy applied to said pair of elongate artificial impedance surface antennas has a relative 90° phase difference.

15. A method of simultaneously receiving two oppositely handed circularly polarized RF signals comprising the steps of: sending the signals received by two SWGs into two input ports of a coupler, the coupler also having two output ports; and extracting LHCP and RHCP signals from the output two ports of the hybrid coupler.

16. The method of claim 15 wherein the coupler is a 3dB 90 degree hybrid coupler.
A. CLASSIFICATION OF SUBJECT MATTER
HOIQ 1/24(2006.01)i, HOIQ 21/06(2006.01)i, HOIQ 9/04(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
HOIQ 1/24; HOIQ 1/50; HOIQ 1/00; G06F 17/50; H01Q 13/00; H01P 5/08; H01Q 9/28; H01Q 21/24; H01Q 21/06; H01Q 9/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS (KIPO internal) & Keywords: antenna, dual-polarization, circularly-polarized, surface-wave, artificial-impedance-surface

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>3,13-14</td>
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<tr>
<td>A</td>
<td>US 2012-0194399 A1 (ADAM BILY et al.) 02 August 2012 See abstract, claims 1-3 and figures 1-12.</td>
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Further documents are listed in the continuation of Box C.

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
  "E" earlier application or patent but published on or after the international filing date
  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  "O" document referring to an oral disclosure, use, exhibition or other means
  "P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
22 September 2015 (22.09.2015)

Date of mailing of the international search report
22 September 2015 (22.09.2015)

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Form PCT/ISA/210 (second sheet) (January 2015)
### Box No. II  Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. □ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. □ Claims Nos.: 7-9
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
   Claims 7-9 are unclear, because they refer to multiple dependent claims which do not comply with PCT Rule 6.4(a).

3. □ Claims Nos.: 4-6, 10-12
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

### Box No. III  Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. □ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. □ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. □ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. □ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

### Remark on Protest

- □ The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.
- □ The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- □ No protest accompanied the payment of additional search fees.
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Form PCT/ISA/2 10 (patent family annex) (January 2015)