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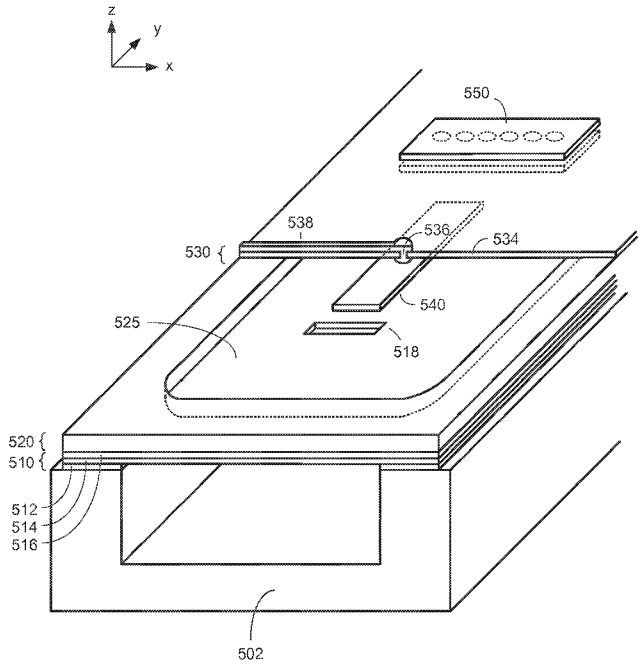
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(54) Title: SURFACE SCATTERING ANTENNA IMPROVEMENTS

FIG. 5



(57) Abstract: Surface scattering antennas provide adjustable radiation fields by adjustably coupling scattering elements along a wave-propagating structure. In some approaches, the scattering elements are patch elements. In some approaches, the scattering elements are made adjustable by disposing an electrically adjustable material, such as a liquid crystal, in proximity to the scattering elements. Methods and systems provide control and adjustment of surface scattering antennas for various applications.

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Surface Scattering Antenna Improvements

All subject matter of the Priority Applications and the Related Applications and of any and all parent, grandparent, great-grandparent, etc. applications of the Priority Applications and the Related applications, including any priority claims, is incorporated herein by reference to the extent such subject matter is not inconsistent herewith.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a schematic depiction of a surface scattering antenna.

FIGS. 2A and **2B** respectively depict an exemplary adjustment pattern and corresponding beam pattern for a surface scattering antenna.

FIGS. 3A and **3B** respectively depict another exemplary adjustment pattern and corresponding beam pattern for a surface scattering antenna.

FIGS. 4A and **4B** respectively depict another exemplary adjustment pattern and corresponding field pattern for a surface scattering antenna.

FIG. 5 depicts an embodiment of a surface scattering antenna including a patch element.

FIGS. 6A and **6B** depict examples of patch elements on a waveguide.

FIG. 6C depicts field lines for a waveguide mode.

FIG. 7 depicts a liquid crystal arrangement.

FIGS. 8A and **8B** depict exemplary counter-electrode arrangements.

FIG. 9 depicts a surface scattering antenna with direct addressing of the scattering elements.

FIG. 10 depicts a surface scattering antenna with matrix addressing of the scattering elements.

FIG. 10 depicts a surface scattering antenna with matrix addressing of the scattering elements.

FIGS. 11A, **12A**, and **13** depict various bias voltage drive schemes.

FIGS. 11B and **12B** depict bias voltage drive circuitry.

FIG. 14 depicts a system block diagram.

FIGS. **15** and **16** depict flow diagrams.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here.

A schematic illustration of a surface scattering antenna is depicted in **FIG. 1**. The surface scattering antenna **100** includes a plurality of scattering elements **102a**, **102b** that are distributed along a wave-propagating structure **104**. The wave propagating structure **104** may be a microstrip, a coplanar waveguide, a parallel plate waveguide, a dielectric slab, a closed or tubular waveguide, or any other structure capable of supporting the propagation of a guided wave or surface wave **105** along or within the structure. The wavy line **105** is a symbolic depiction of the guided wave or surface wave, and this symbolic depiction is not intended to indicate an actual wavelength or amplitude of the guided wave or surface wave; moreover, while the wavy line **105** is depicted as within the wave-propagating structure **104** (e.g. as for a guided wave in a metallic waveguide), for a surface wave the wave may be substantially localized outside the wave-propagating structure (e.g. as for a TM mode on a single wire transmission line or a "spoof plasmon" on an artificial impedance surface). The scattering elements **102a**, **102b** may include scattering elements that are embedded within, positioned on a surface of, or positioned within an evanescent proximity of, the wave-propagation structure **104**. For example, the scattering elements can include complementary metamaterial elements such as those presented in D. R. Smith et al, "Metamaterials for surfaces and waveguides," U.S. Patent Application Publication No. 2010/0156573, and A. Bily et al, "Surface scattering antennas," U.S. Patent Application Publication No. 2012/0194399, each of which is herein incorporated by reference. As another example, the scattering elements can include patch elements, as discussed below.

The surface scattering antenna also includes at least one feed connector **106** that is configured to couple the wave-propagation structure **104** to a feed structure **108**. The feed structure **108** (schematically depicted as a coaxial cable) may be a transmission line, a waveguide, or any other structure capable of providing an electromagnetic signal that may be launched, via the feed connector **106**, into a guided wave or surface wave **105** of the wave-propagating structure **104**. The feed connector **106** may be, for example, a coaxial-to-microstrip connector (e.g. an SMA-to-PCB adapter), a coaxial-to-waveguide connector, a mode-matched transition section, etc.. While **FIG. 1** depicts the feed connector in an "end-launch" configuration, whereby the guided wave or surface wave **105** may be launched from a peripheral region of the wave-propagating structure (e.g. from an end of a microstrip or from an edge of a parallel plate waveguide), in other embodiments the feed structure may be attached to a non-peripheral portion of the wave-propagating structure, whereby the guided wave or surface wave **105** may be launched from that non-peripheral portion of the wave-propagating structure (e.g. from a midpoint of a microstrip or through a hole drilled in a top or bottom plate of a parallel plate waveguide); and yet other embodiments may provide a plurality of feed connectors attached to the wave-propagating structure at a plurality of locations (peripheral and/or non-peripheral).

The scattering elements **102a**, **102b** are adjustable scattering elements having electromagnetic properties that are adjustable in response to one or more external inputs. Various embodiments of adjustable scattering elements are described, for example, in D. R. Smith et al, previously cited, and further in this disclosure. Adjustable scattering elements can include elements that are adjustable in response to voltage inputs (e.g. bias voltages for active elements (such as varactors, transistors, diodes) or for elements that incorporate tunable dielectric materials (such as ferroelectrics or liquid crystals)), current inputs (e.g. direct injection of charge carriers into active elements), optical inputs (e.g. illumination of a photoactive material), field inputs (e.g. magnetic fields for elements that include nonlinear magnetic materials), mechanical inputs (e.g. MEMS, actuators, hydraulics), etc. In the schematic example of **FIG. 1**, scattering elements that have been adjusted to a first state having first

electromagnetic properties are depicted as the first elements **102a**, while scattering elements that have been adjusted to a second state having second electromagnetic properties are depicted as the second elements **102b**. The depiction of scattering elements having first and second states corresponding to first and second electromagnetic properties is not intended to be limiting: embodiments may provide scattering elements that are discretely adjustable to select from a discrete plurality of states corresponding to a discrete plurality of different electromagnetic properties, or continuously adjustable to select from a continuum of states corresponding to a continuum of different electromagnetic properties. Moreover, the particular pattern of adjustment that is depicted in **FIG. 1** (i.e. the alternating arrangement of elements **102a** and **102b**) is only an exemplary configuration and is not intended to be limiting.

In the example of **FIG. 1**, the scattering elements **102a**, **102b** have first and second couplings to the guided wave or surface wave **105** that are functions of the first and second electromagnetic properties, respectively. For example, the first and second couplings may be first and second polarizabilities of the scattering elements at the frequency or frequency band of the guided wave or surface wave. In one approach the first coupling is a substantially nonzero coupling whereas the second coupling is a substantially zero coupling. In another approach both couplings are substantially nonzero but the first coupling is substantially greater than (or less than) than the second coupling. On account of the first and second couplings, the first and second scattering elements **102a**, **102b** are responsive to the guided wave or surface wave **105** to produce a plurality of scattered electromagnetic waves having amplitudes that are functions of (e.g. are proportional to) the respective first and second couplings. A superposition of the scattered electromagnetic waves comprises an electromagnetic wave that is depicted, in this example, as a plane wave **110** that radiates from the surface scattering antenna **100**.

The emergence of the plane wave may be understood by regarding the particular pattern of adjustment of the scattering elements (e.g. an alternating arrangement of the first and second scattering elements in **FIG. 1**) as a pattern that defines a grating that scatters the guided wave or surface wave **105** to produce the plane wave **110**. Because this pattern is adjustable, some embodiments of the surface

scattering antenna may provide adjustable gratings or, more generally, holograms, where the pattern of adjustment of the scattering elements may be selected according to principles of holography. Suppose, for example, that the guided wave or surface wave may be represented by a complex scalar input wave Ψ_{in} that is a function of position along the wave-propagating structure **104**, and it is desired that the surface scattering antenna produce an output wave that may be represented by another complex scalar wave Ψ_{out}. Then a pattern of adjustment of the scattering elements may be selected that corresponds to an interference pattern of the input and output waves along the wave-propagating structure. For example, the scattering elements may be adjusted to provide couplings to the guided wave or surface wave that are functions of (e.g. are proportional to, or step-functions of) an interference term given by $\mathrm{Re}[\Psi_{out}\Psi_{in}^{*}]$. In this way, embodiments of the surface scattering antenna may be adjusted to provide arbitrary antenna radiation patterns by identifying an output wave Ψ_{out} corresponding to a selected beam pattern, and then adjusting the scattering elements accordingly as above. Embodiments of the surface scattering antenna may therefore be adjusted to provide, for example, a selected beam direction (e.g. beam steering), a selected beam width or shape (e.g. a fan or pencil beam having a broad or narrow beamwidth), a selected arrangement of nulls (e.g. null steering), a selected arrangement of multiple beams, a selected polarization state (e.g. linear, circular, or elliptical polarization), a selected overall phase, or any combination thereof. Alternatively or additionally, embodiments of the surface scattering antenna may be adjusted to provide a selected near field radiation profile, e.g. to provide near-field focusing and/or near-field nulls.

Because the spatial resolution of the interference pattern is limited by the spatial resolution of the scattering elements, the scattering elements may be arranged along the wave-propagating structure with inter-element spacings that are much less than a free-space wavelength corresponding to an operating frequency of the device (for example, less than one-third, one-fourth, or one-fifth of this free-space wavelength). In some approaches, the operating frequency is a microwave frequency, selected from frequency bands such as L, S, C, X, Ku, K, Ka, Q, U, V, E, W, F, and

D, corresponding to frequencies ranging from about 1 GHz to 170 GHz and free-space wavelengths ranging from millimeters to tens of centimeters. In other approaches, the operating frequency is an RF frequency, for example in the range of about 100 MHz to 1 GHz. In yet other approaches, the operating frequency is a millimeter-wave frequency, for example in the range of about 170 GHz to 300 GHz. These ranges of length scales admit the fabrication of scattering elements using conventional printed circuit board or lithographic technologies.

In some approaches, the surface scattering antenna includes a substantially one-dimensional wave-propagating structure **104** having a substantially one-dimensional arrangement of scattering elements, and the pattern of adjustment of this one-dimensional arrangement may provide, for example, a selected antenna radiation profile as a function of zenith angle (i.e. relative to a zenith direction that is parallel to the one-dimensional wave-propagating structure). In other approaches, the surface scattering antenna includes a substantially two-dimensional wave-propagating structure **104** having a substantially two-dimensional arrangement of scattering elements, and the pattern of adjustment of this two-dimensional arrangement may provide, for example, a selected antenna radiation profile as a function of both zenith and azimuth angles (i.e. relative to a zenith direction that is perpendicular to the two-dimensional wave-propagating structure). Exemplary adjustment patterns and beam patterns for a surface scattering antenna that includes a two-dimensional array of scattering elements distributed on a planar rectangular wave-propagating structure are depicted in **FIGS. 2A – 4B**. In these exemplary embodiments, the planar rectangular wave-propagating structure includes a monopole antenna feed that is positioned at the geometric center of the structure. **FIG. 2A** presents an adjustment pattern that corresponds to a narrow beam having a selected zenith and azimuth as depicted by the beam pattern diagram of **FIG. 2B**. **FIG. 3A** presents an adjustment pattern that corresponds to a dual-beam far field pattern as depicted by the beam pattern diagram of **FIG. 3B**. **FIG. 4A** presents an adjustment pattern that provides near-field focusing as depicted by the field intensity map of **FIG. 4B** (which depicts the field intensity along a plane perpendicular to and bisecting the long dimension of the rectangular wave-propagating structure).

In some approaches, the wave-propagating structure is a modular wave-propagating structure and a plurality of modular wave-propagating structures may be assembled to compose a modular surface scattering antenna. For example, a plurality of substantially one-dimensional wave-propagating structures may be arranged, for example, in an interdigital fashion to produce an effective two-dimensional arrangement of scattering elements. The interdigital arrangement may comprise, for example, a series of adjacent linear structures (i.e. a set of parallel straight lines) or a series of adjacent curved structures (i.e. a set of successively offset curves such as sinusoids) that substantially fills a two-dimensional surface area. These interdigital arrangements may include a feed connector having a tree structure , e.g. a binary tree providing repeated forks that distribute energy from the feed structure **108** to the plurality of linear structures (or the reverse thereof). As another example, a plurality of substantially two-dimensional wave-propagating structures (each of which may itself comprise a series of one-dimensional structures, as above) may be assembled to produce a larger aperture having a larger number of scattering elements; and/or the plurality of substantially two-dimensional wave-propagating structures may be assembled as a three-dimensional structure (e.g. forming an A-frame structure, a pyramidal structure, or other multi-faceted structure). In these modular assemblies, each of the plurality of modular wave-propagating structures may have its own feed connector(s) **106**, and/or the modular wave-propagating structures may be configured to couple a guided wave or surface wave of a first modular wave-propagating structure into a guided wave or surface wave of a second modular wave-propagating structure by virtue of a connection between the two structures.

In some applications of the modular approach, the number of modules to be assembled may be selected to achieve an aperture size providing a desired telecommunications data capacity and/or quality of service, and/or a three-dimensional arrangement of the modules may be selected to reduce potential scan loss. Thus, for example, the modular assembly could comprise several modules mounted at various locations/orientations flush to the surface of a vehicle such as an aircraft, spacecraft, watercraft, ground vehicle, etc. (the modules need not be contiguous). In these and other approaches, the wave-propagating structure may have

a substantially non-linear or substantially non-planar shape whereby to conform to a particular geometry, therefore providing a conformal surface scattering antenna (conforming, for example, to the curved surface of a vehicle).

More generally, a surface scattering antenna is a reconfigurable antenna that may be reconfigured by selecting a pattern of adjustment of the scattering elements so that a corresponding scattering of the guided wave or surface wave produces a desired output wave. Suppose, for example, that the surface scattering antenna includes a plurality of scattering elements distributed at positions $\{\mathbf{r}_j\}$ along a wave-propagating structure **104** as in **FIG. 1** (or along multiple wave-propagating structures, for a modular embodiment) and having a respective plurality of adjustable couplings $\{\alpha_j\}$ to the guided wave or surface wave **105**. The guided wave or surface wave **105**, as it propagates along or within the (one or more) wave-propagating structure(s), presents a wave amplitude A_j and phase φ_j to the jth scattering element; subsequently, an output wave is generated as a superposition of waves scattered from the plurality of scattering elements:

$$\mathbf{E}(\theta,\phi) = \sum_j \mathbf{R}_j(\theta,\phi)\alpha_j A_j e^{i\varphi_j} e^{j(\mathbf{k}(\theta,\phi)\cdot\mathbf{r}_j)}, \qquad (1)$$

where $\mathbf{E}(\theta,\phi)$ represents the electric field component of the output wave on a far-field radiation sphere, $\mathbf{R}_j(\theta,\phi)$ represents a (normalized) electric field pattern for the scattered wave that is generated by the jth scattering element in response to an excitation caused by the coupling α_j, and $\mathbf{k}(\theta,\phi)$ represents a wave vector of magnitude ω/c that is perpendicular to the radiation sphere at (θ,ϕ). Thus, embodiments of the surface scattering antenna may provide a reconfigurable antenna that is adjustable to produce a desired output wave $\mathbf{E}(\theta,\phi)$ by adjusting the plurality of couplings $\{\alpha_j\}$ in accordance with equation (1).

The wave amplitude A_j and phase φ_j of the guided wave or surface wave are functions of the propagation characteristics of the wave-propagating structure **104**. These propagation characteristics may include, for example, an effective refractive index and/or an effective wave impedance, and these effective electromagnetic

properties may be at least partially determined by the arrangement and adjustment of the scattering elements along the wave-propagating structure. In other words, the wave-propagating structure, in combination with the adjustable scattering elements, may provide an adjustable effective medium for propagation of the guided wave or surface wave, e.g. as described in D. R. Smith et al, previously cited. Therefore, although the wave amplitude A_j and phase φ_j of the guided wave or surface wave may depend upon the adjustable scattering element couplings $\{\alpha_j\}$ (i.e. $A_i = A_i(\{\alpha_j\})$, $\varphi_i = \varphi_i(\{\alpha_j\})$), in some embodiments these dependencies may be substantially predicted according to an effective medium description of the wave-propagating structure.

In some approaches, the reconfigurable antenna is adjustable to provide a desired polarization state of the output wave $\mathbf{E}(\theta,\phi)$. Suppose, for example, that first and second subsets $LP^{(1)}$ and $LP^{(2)}$ of the scattering elements provide (normalized) electric field patterns $\mathbf{R}^{(1)}(\theta,\phi)$ and $\mathbf{R}^{(2)}(\theta,\phi)$, respectively, that are substantially linearly polarized and substantially orthogonal (for example, the first and second subjects may be scattering elements that are perpendicularly oriented on a surface of the wave-propagating structure **104**). Then the antenna output wave $\mathbf{E}(\theta,\phi)$ may be expressed as a sum of two linearly polarized components:

$$\mathbf{E}(\theta,\phi) = \mathbf{E}^{(1)}(\theta,\phi) + \mathbf{E}^{(2)}(\theta,\phi) = \Lambda^{(1)}\mathbf{R}^{(1)}(\theta,\phi) + \Lambda^{(2)}\mathbf{R}^{(2)}(\theta,\phi), \qquad (2)$$

where

$$\Lambda^{(1,2)}(\theta,\phi) = \sum_{j\in LP^{(1,2)}} \alpha_j A_j e^{i\varphi_j} e^{i(\mathbf{k}(\theta,\phi)\cdot\mathbf{r}_j)} \qquad (3)$$

are the complex amplitudes of the two linearly polarized components. Accordingly, the polarization of the output wave $\mathbf{E}(\theta,\phi)$ may be controlled by adjusting the plurality of couplings $\{\alpha_j\}$ in accordance with equations (2)-(3), e.g. to provide an output wave with any desired polarization (e.g. linear, circular, or elliptical).

Alternatively or additionally, for embodiments in which the wave-propagating structure has a plurality of feeds (e.g. one feed for each "finger" of an interdigital arrangement of one-dimensional wave-propagating structures, as discussed above), a

desired output wave $\mathbf{E}(\theta,\phi)$ may be controlled by adjusting gains of individual amplifiers for the plurality of feeds. Adjusting a gain for a particular feed line would correspond to multiplying the A_j's by a gain factor G for those elements j that are fed by the particular feed line. Especially, for approaches in which a first wave-propagating structure having a first feed (or a first set of such structures/feeds) is coupled to elements that are selected from $LP^{(1)}$ and a second wave-propagating structure having a second feed (or a second set of such structures/feeds) is coupled to elements that are selected from $LP^{(2)}$, depolarization loss (e.g., as a beam is scanned off-broadside) may be compensated by adjusting the relative gain(s) between the first feed(s) and the second feed(s).

As mentioned previously in the context of **FIG. 1**, in some approaches the surface scattering antenna **100** includes a wave-propagating structure **104** that may be implemented as a closed waveguide (or a plurality of closed waveguides); and in these approaches, the scattering elements may include complementary metamaterial elements or patch elements. Exemplary closed waveguides that include complementary metamaterial elements are depicted in Figures 10 and 11 of A. Bily et al, previously cited. Another exemplary closed waveguide embodiment that includes patch elements is presently depicted in **FIG. 5.** In this embodiment, a closed waveguide with a rectangular cross section is defined by a trough **502** and a first printed circuit board **510** having three layers: a lower conductor **512**, a middle dielectric **514**, and an upper conductor **516**. The upper and lower conductors may be electrically connected by stitching vias (not shown). The trough **502** can be implemented as a piece of metal that is milled or cast to provide the "floor and walls" of the closed waveguide, with the first printed circuit board **510** providing the waveguide "ceiling." Alternatively, the trough **502** may be implemented with an epoxy laminate material (such as FR-4) in which the waveguide channel is routed or machined and then plated (e.g. with copper) using a process similar to a standard PCB through hole/via process. Overlaid on the first printed circuit board **510** are a dielectric spacer **520** and second printed circuit board **530**. As the unit cell cutaway shows, the conducting surface **516** has an iris **518** that permits coupling between a guided wave and the resonator element **540**, which in this case is a rectangular patch

element disposed on the lower surface of the second printed circuit board **530**. A via **536** through the dielectric layer **534** of the second printed circuit board **530** can be used to connect a bias voltage line **538** to the patch element **540**. The patch element **540** may be optionally bounded by collonades of vias **550** extended through the dielectric layer **534** to reduce coupling or crosstalk between adjacent unit cells. The dielectric spacer **520** includes a cutout region **525** between the iris **518** and the patch **540**, and this cutout region is filled with an electrically tunable medium (such as a liquid crystal medium) to accomplish tuning of the cell resonance.

While the waveguide embodiment of **FIG. 5** provides a waveguide having a simple rectangular cross section, in some approaches the waveguide may include one or more ridges (as in a double-ridged waveguide). Ridged waveguides can provide greater bandwidth than simple rectangular waveguides and the ridge geometries (widths/heights) can be varied along the length of the waveguide to control the couplings to the scattering elements (e.g. to enhance aperture efficiency and/or control aperture tapering of the beam profile) and/or to provide a smooth impedance transition (e.g. from an SMA connector feed). Alternatively or additionally, the waveguide may be loaded with a dielectric material (such as PTFE). This dielectric material can occupy all or a portion of the waveguide cross section, and the amount of the cross section that is occupied can also be tapered along the length of the waveguide.

While the example of **FIG. 5** depicts a rectangular patch **540** fed by a narrow iris **518**, a variety of patch and iris geometries may be used, with exemplary configurations depicted in **FIG. 6A-6B**. These figures depict the placement of patches **601** and irises **602** when viewed looking down upon a closed waveguide **610** having a center axis **612**. **FIG. 6A** shows rectangular patches **601** oriented along the y-direction and edge-fed by slit-like irises **602** oriented along the x-direction. **FIG. 6B** shows hexagonal patches **601** center-fed by circular irises **602**. The hexagonal patches may include notches **603** to adjust the resonant frequencies of the patches. It will be appreciated that the irises and patches can take a variety of other shapes including rectangles, squares, ellipses, circles, or polygons, with or without notches or tabs to adjust resonant frequencies, and that the relative lateral (x and/or y) position

between patch and iris may be adjusted to achieve a desired patch response, e.g. edge-fed or center-fed. For example, an offset feed may be used to stimulate circularly polarization radiation. The positions, shapes, and/or sizes of the irises and/or patches can be gradually adjusted or tapered along the length of the waveguide, to control the waveguide couplings to the patch elements (e.g. to enhance overall aperture efficiency and/or control aperture tapering of the beam profile).

Because the irises **602** couple the patches **601** to the guided wave mode by means of the H-field that is present at the upper surface of the waveguide, the irises can be particularly positioned along the y-direction (perpendicular to the waveguide) to exploit the pattern of this H-field at the upper surface of the waveguide. **FIG. 6C** depicts this H-field pattern for the dominant TE10 mode of a rectangular waveguide. On the center axis **612** of the waveguide, the H-field is entirely directed along the x-direction, whereas at the edge **614** of the waveguide, the H-field is entirely directed along the y-direction. For a slit-like iris oriented along the x-direction, the iris-mediated coupling between the patch and the waveguide can be adjusted by changing the x-position of the iris; thus, for example, slit-like irises can be positioned equidistant from the center axis **612** on left and right sides of the waveguide for equal coupling, as in **FIG. 6A**. This x-positioning of the irises can also be gradually adjusted or tapered along the length of the waveguide, to control the couplings to the patch elements (e.g. to enhance overall aperture efficiency and/or control aperture tapering of the beam profile).

For positions intermediate between the center axis **612** and the edge **614** in **FIG. 6C**, the H-field has both x and y components and sweeps out an ellipse at a fixed iris location as the guided wave mode propagates along the waveguide. Thus, the iris-mediated coupling between the patch and the waveguide can be adjusted by changing the x-position of the iris: changing the distance from the center axis **612** adjusts the eccentricity of the coupled H-field, which switching from one side of the center axis to the other side reverses the direction of rotation of the coupled H-field.

In one approach, the rotation of the H-field for a fixed position away from the center axis **612** of the waveguide can be exploited to provide a beam that is circularly polarized by virtue of this H-field rotation. A patch with two resonant modes having

mutually orthogonal polarization states can leverage the rotation of the H-field excitation to result in a circular or elliptical polarization. For example, for a guided wave TE10 mode that propagates in the +y direction of **FIG. 6C**, positioning an iris and center-fed square or circular patch halfway between the center axis and the left edge of the waveguide will yield a right-circular-polarized radiation pattern for the patch, while positioning the iris and center-fed square or circular patch halfway between the center axis and the right edge of the waveguide will yield a left-circular-polarized radiation pattern for the patch. Thus, the antenna may be switched between polarization states by switching from active elements on the left half of the waveguide to active elements on the right half of the waveguide or vice versa, or by reversing the direction of propagation of the guided wave TE10 mode (e.g. by feeding the waveguide from the opposite end).

Alternatively, for scattering elements that yield linear polarization patterns, as for the configuration of **FIG. 6A**, the linear polarization may be converted to circular polarization by placing a linear-to-circular polarization conversion structure above the scattering elements. For example, a quarter-wave plate or meander-line structure may be positioned above the scattering elements. Quarter-wave plates may include anisotropic dielectric materials (see, e.g., H.S. Kirschbaum and S. Chen, "A Method of Producing Broad-Band Circular Polarization Employing an Anisotropic Dielectric," IRE Trans. Micro. Theory. Tech., Vol. 5, No. 3, pp. 199-203, 1957; J. Y. Chin et al, "An efficient broadband metamaterial wave retarder," Optics Express, Vol. 17, No. 9, pp. 7640-7647, 2009), and/or may also be implemented as artificial magnetic materials (see, e.g., Dunbao Yan et al, "A Novel Polarization Convert Surface Based on Artificial Magnetic Conductor," Asia-Pacific Microwave Conference Proceedings, 2005). Meander-line polarizers typically consist of two, three, four, or more layers of conducting meander line arrays (e.g. copper on a thin dielectric substrate such as Duroid), with interleaved spacer layers (e.g. closed-cell foam). Meander-line polarizers may be designed and implemented according to known techniques, for example as described in Young, et. al., "Meander-Line Polarizer," IEEE Trans. Ant. Prop., pp. 376-378, May 1973 and in R.S. Chu and K.M. Lee, "Analytical Model of a Multilayered Meander-Line Polarizer Plate with Normal

and Oblique Plane-Wave Incidence," IEEE Trans. Ant. Prop., Vol. AP-35, No.6, pp. 652-661, June 1987. In embodiments that include a linear-to-circular polarization conversion structure, the conversion structure may be incorporated into, or may function as, a radome providing environmental insulation for the antenna. Moreover, the conversion structure may be flipped over to reverse the polarization state of the transmitted or received radiation.

The electrically tunable medium that occupies the cutaway region **125** between the iris **118** and patch **140** in **FIG. 6** may include a liquid crystal. Liquid crystals have a permittivity that is a function of orientation of the molecules comprising the liquid crystal; and that orientation may be controlled by applying a bias voltage (equivalently, a bias electric field) across the liquid crystal; accordingly, liquid crystals can provide a voltage-tunable permittivity for adjustment of the electromagnetic properties of the scattering element. Exemplary liquid crystals that may be deployed in various embodiments include 4-Cyano-4'-pentylbiphenyl and high birefringence eutectic LC mixtures such as LCMS-107 (LC Matter) or GT3-23001 (Merck).

Some approaches may utilize dual-frequency liquid crystals. In dual-frequency liquid crystals, the liquid crystal director aligns substantially parallel to an applied bias field at a lower frequencies, but substantially perpendicular to an applied bias field at higher frequencies. Accordingly, for approaches that deploy these dual-frequency liquid crystals, tuning of the scattering elements may be accomplished by adjusting the frequency of the applied bias voltage signals.

Other approaches may deploy polymer network liquid crystals (PNLCs) or polymer dispersed liquid crystals (PDLCs), which generally provide much shorter relaxation/switching times for the liquid crystal. An example is a thermal or UV cured mixture of a polymer (such as BPA-dimethacrylate) in a nematic LC host (such as LCMS-107); cf. Y.H. Fan et al, "Fast-response and scattering-free polymer network liquid crystals for infrared light modulators," *Applied Physics Letters* **84**, 1233-35 (2004), herein incorporated by reference. Whether the polymer-liquid crystal mixture is described as a PNLC or a PDLC depends upon the relative

concentration of polymer and liquid crystal, the latter having a higher concentration of polymer whereby the LC is confined in the polymer network as droplets.

Some approaches may include a liquid crystal that is embedded within an interstitial medium. An example is a porous polymer material (such as a PTFE membrane) impregnated with a nematic LC (such as LCMS-107); cf. T. Kuki et al, "Microwave variable delay line using a membrane impregnated with liquid crystal," *Microwave Symposium Digest, 2002 IEEE MTT-S International* , vol.1, pp.363-366 (2002), herein incorporated by reference.

The interstitial medium is preferably a porous material that provides a large surface area for strong surface alignment of the unbiased liquid crystal. Examples of such porous materials include ultra high molecular weight polyethylene (UHMW-PE) and expanded polytetraflouroethylene (ePTFE) membranes that have been treated to be hydrophilic. Specific examples of such interstitial media include Advantec MFS Inc., Part # H020A047A (hydrophilic ePTFE) and DeWal Industries 402P (UHMW-PE).

In the patch arrangement of **FIG. 5**, it may be seen that the voltage biasing of the patch antenna relative to the conductive surface **516** containing the iris **518** will induce a substantially vertical (z-direction) alignment of the liquid crystal that occupies the cutaway region **525**. Accordingly, to enhance the tuning effect, it may be desirable to arrange the interstitial medium and/or alignment layers to provide an unbiased liquid crystal alignment that is substantially horizontal (e.g. in the y direction). An example of such an arrangement is depicted in **FIG. 7**, which shows an exploded diagram of the same elements as in **FIG. 5**. In this example, the upper conductor **516** of the lower circuit board presents a lower alignment layer **701** that is aligned along the y-direction. This alignment layer may be implemented by, for example, coating the lower circuit board with a polyimide layer and rubbing or otherwise patterning (e.g. by machining or photolithography) the polyimide layer to introduce microscopic grooves that run parallel to the y-direction. Similarly, the upper dielectric **534** and patch **540** present an upper alignment layer **702** that is also aligned along the y-direction. A liquid-crystal-impregnated interstitial medium **703** fills the cutaway region **525** of the spacer layer **520**; as depicted schematically in the

figure, the interstitial medium may be designed and arranged to include microscopic pores **710** that extend along the y-direction to present a large surface area for the liquid crystal that is substantially along the y-direction.

In some approaches, it may be desirable to introduce one or more counter-electrodes into the unit cell, so that the unit cell can provide both a first biasing that aligns the liquid crystal substantially parallel to the electric field lines of the unit cell resonance mode, and a second biasing ("counter-biasing") that aligns the liquid crystal substantially perpendicular to the electric field lines of the unit cell resonance mode. One advantage of introducing counter-biasing is that that the unit cell tuning speed is then no longer limited by a passive relaxation time of the liquid crystal.

For purposes of characterizing counter-electrode arrangements, it is useful to distinguish between in-plane switching schemes, where the resonators are defined by conducting islands coplanar with a ground plane (e.g. as with the so-called "CELC" resonators, such as those described in A. Bily et al, previously cited), and vertical switching schemes, where the resonators are defined by patches positioned vertically above a ground plane containing irises (e.g. as in **FIG. 5**).

A counter-electrode arrangement for an in-plane switching scheme is depicted in **FIG. 8A**, which shows a unit cell resonator defined by an inner electrode or conducting island **801** and an outer electrode or ground plane **802**. The liquid crystal material **810** is enclosed above the resonator by an enclosing structure **820**, e.g. a polycarbonate container. In the exemplary counter-electrode arrangement of **FIG. 8A**, the counter-electrode is provided as a very thin layer **830** of a conducting material such as chromium or titanium, deposited on the upper surface of the enclosing structure **820**. The layer is thin enough (e.g. 10-30 nm) to introduce only small loss at antenna operating frequencies, but sufficiently conductive that the (1/RC) charging rate is small compared to the unit cell update rate. In other approaches, the conducting layer is an organic conductor such as polyacetylene, which can be spin-coated on the enclosing structure **820**. In yet other approaches, the conducting layer is an anisotropic conducting layer, i.e. having two conductivities σ_1 and σ_2 for two orthogonal directions along the layer, and the anisotropic conducting layer may be aligned relative to the unit cell resonator so that the effective

conductivity seen by the unit cell resonator is minimized. For example, the anisotropic conducting layer may consist of wires or stripes that are aligned substantially perpendicular to the electric field lines of the unit cell resonance mode.

By applying a first bias corresponding to a voltage differential V_i-V_o between the inner electrode **801** and outer electrode **802**, a first (substantially horizontal) bias electric field **840** is established, substantially parallel to electric field lines of the unit cell resonance mode. On the other hand, by applying a second bias corresponding to a voltage differential V_c-V_i=V_c-V_o between the counter-electrode **830** and the inner and outer electrodes **801** and **802**, a second (substantially vertical) bias electric field **842** is established, substantially perpendicular to electric field lines of the unit cell resonance mode.

In some approaches, the second bias may be applied for a duration shorter than a relaxation time of the liquid crystal; for example, the second bias may be applied for less than one-half or one-third of this relaxation time. One advantage of this approach is that while the application of the second bias seeds the relaxation of the liquid crystal, it may be preferable to have the liquid crystal then relax to an unbiased state rather than align according to the bias electric field.

A counter-electrode arrangement for a vertical switching scheme is depicted in **FIG. 8B**, which shows a unit cell resonator defined by an upper patch **804** and a lower ground plane **805** containing an iris **806**. The liquid crystal material **810** is enclosed within the region between the upper dielectric layer **808** (supporting the upper patch **804**) and the lower dielectric layer **809** (supporting the lower ground plane **805**). In the exemplary counter-electrode arrangement of **FIG. 8B**, the counter-electrode is provided as a very thin layer **830** of a conducting material such as chromium or titanium, deposited on the lower surface of the upper dielectric layer **808**. The layer is thin enough (e.g. 10-30 nm) to introduce only small loss at antenna operating frequencies, but sufficiently conductive that the (1/RC) charging rate is small compared to the unit cell update rate. Other approaches may use organic conductors or anisotropic conducting layers, as described above.

By applying a first bias corresponding to a voltage differential V_u-V_l=V_c-V_l between the upper and counter electrodes **804** and **830** and lower electrode **805**, a first

(substantially vertical) bias electric field **844** is established, substantially parallel to electric field lines of the unit cell resonance mode. On the other hand, by applying a second bias corresponding to a voltage differential V_c-V_u between the counter electrode **830** and the upper electrode **804**, a second (substantially horizontal) bias electric field **846** is established, substantially perpendicular to electric field lines of the unit cell resonance mode. Again, in some approaches, the second bias may be applied for a duration shorter than a relaxation time of the liquid crystal, for the same reason as discussed above for horizontal switching. In various embodiments of the vertical switching scheme, the counter-electrode **830** may constitute a pair of electrodes on opposite sides of the patch **804**, or a U-shaped electrode that surrounds three sides of the patch **804**, or a closed loop that surrounds all four sides of the patch **804**.

In various approaches, the bias voltage lines may be directly addressed, e.g. by extending a bias voltage line for each scattering element to a pad structure for connection to antenna control circuitry, or matrix addressed, e.g. by providing each scattering element with a voltage bias circuit that is addressable by row and column. **FIG. 9** depicts an example of a configuration that provides direct addressing for an arrangement of scattering elements **900**, in which a plurality of bias voltage lines **904** deliver individual bias voltages to the scattering elements. **FIG. 10** depicts an example of a configuration that provides matrix addressing for an arrangement of scattering elements **1000**, where each scattering element is connected by a bias voltage line **1002** to a biasing circuit **1004** addressable by row inputs **1006** and column inputs **1008** (note that each row input and/or column input may include one or more signals, e.g. each row or column may be addressed by a single wire or a set of parallel wires dedicated to that row or column). Each biasing circuit may contain, for example, a switching device (e.g. a transistor), a storage device (e.g. a capacitor), and/or additional circuitry such as logic/multiplexing circuitry, digital-to-analog conversion circuitry, etc. This circuitry may be readily fabricated using monolithic integration, e.g. using a thin-film transistor (TFT) process, or as a hybrid assembly of integrated circuits that are mounted on the wave-propagating structure, e.g. using surface mount technology (SMT). Although **FIGS. 9** and **10** depict the scattering

elements as "CELC" resonators, this depiction is intended to represent generic scattering elements, and the direct or matrix addressing schemes of **FIGS. 9** and **10** are applicable to other unit cell designs (such as the patch element).

For approaches that use liquid crystal as a tunable medium for the unit cell, it may be desirable to provide unit cell bias voltages that are AC signals with a minimal DC component. Prolonged DC operation can cause electrochemical reactions that significantly reduce the usable lifespan of the liquid crystal as a tunable medium. In some approaches, a unit cell may be tuned by adjusting the amplitude of an AC bias signal. In other approaches, a unit cell may be tuned by adjusting the pulse width of an AC bias signal, e.g. using pulse width modulation (PWM). In yet other approaches, a unit cell may be tuned by adjusting both the amplitude and pulse with of an AC bias signal. Various liquid crystal drive schemes have been extensively explored in the liquid crystal display literature, for example as described in Robert Chen, *Liquid Crystal Displays,* Wiley, New Jersey, 2011, and in Willem den Boer, *Active Matrix Liquid Crystal Displays*, Elsevier, Burlington, MA 2009.

Exemplary waveforms for a binary (ON-OFF) bias voltage adjustment scheme are depicted in **FIG. 11A**. In this binary scheme, a first square wave voltage V_i is applied to inner electrode **1111** of a unit cell **1110**, and a second square wave voltage V_o is applied to outer electrode **1112** of the unit cell. Although the figure depicts a "CELC" resonator defined by a conducting island (inner electrode) coplanar with a ground plane (outer electrode), this depiction is intended to represent a generic unit cell, and the drive scheme is applicable to other unit cell designs. For example, for a "patch" resonator defined by a conducting patch positioned vertically above an iris in a ground plane, the first square wave voltage V_i may be applied to the patch, while the second square wave voltage V_o may be applied to the ground plane.

In the binary scheme of **FIG. 11A**, the unit cell is biased "ON" when the two square waves are 180° out of phase with each other, with the result that the potential applied to the liquid crystal, $V_{LC} = V_i - V_o$, is a square wave with zero DC offset, as shown in the top right panel of the figure. On the other hand, the unit cell is biased "OFF" when the two square waves are in phase with each other, with the result that $V_{LC} = 0$, as shown in the bottom right panel of the figure. The square wave amplitude

VPP is a voltage large enough to effect rapid alignment of the liquid crystal, typically in the range of 10-100 volts. The square wave frequency is a "drive" frequency that is large compared to both the desired antenna switching rate and liquid crystal relaxation rates. The drive frequency can range from as low as 10 Hz to as high as 100 kHz.

Exemplary circuitry providing the waveforms of **FIG. 11A** to a plurality of unit cells is depicted in **FIG. 11B**. In this example, bits representing the "ON" or "OFF" states of the unit cells are read into a N-bit serial-to-parallel shift register **1120** using the DATA and CLK signals. When this serial read-in is complete, the LATCH signal is triggered to store these bits in an N-bit latch **1130**. The N-bit latch outputs, which may be toggled with XOR gates **1140** via the POL signal, provide the inputs for high-voltage push-pull amplifiers **1150** that deliver the waveforms to the unit cells. Note that one or more bits of the shift register may be reserved to provide the waveform for the common outer electrode **1162**, while the remaining bits of the shift register provide the individual waveforms for the inner electrodes **1161** of the unit cells. Alternatively, the entire shift register may be used for inner electrodes **1161**, and a separate push-pull amplifier may be used for the outer electrode **1162**. Square waves may be produced at the outputs of the push-pull amplifiers **1150** by either (1) toggling the XOR gates at the drive frequency (i.e. with a POL signal that is a square wave at the drive frequency) or (2) latching at twice the drive frequency (i.e. with a LATCH signal that is a square wave at twice the drive frequency) while reading in complementary bits during the second half-cycle of each drive period. Under the latter approach, because there is an N-bit read-in during each half-cycle of the drive period, the serial input data is clocked at a frequency not less than $2 \times N \times f$, where f is the drive frequency. The N-bit shift register may address all of the unit cells that compose the antenna, or several N-bit shift registers may be used, each addressing a subset of the unit cells.

The binary scheme of **FIG. 11A** applies voltage waveforms to both the inner and outer electrode of the unit cell. In another approach, shown in **FIG. 12A**, the outer electrode is grounded and a voltage waveform is applied only to the inner electrode of the unit cell. In this single-ended drive approach, the unit cell is biased

"ON" when a square wave with zero DC offset is applied to the inner electrode **1111** (as shown in the top right panel of **FIG. 12A**) and biased "OFF" when a zero voltage is applied to the inner electrode (as shown in the bottom right panel of **FIG. 12A**).

Exemplary circuitry providing the waveforms of **FIG. 12A** to a plurality of unit cells is depicted in **FIG. 12B**. The circuitry is similar to that of **FIG. 11B**, except that the common outer electrode is now grounded, and new oscillating power supply voltages VPP′ and VDD′ are used for the high-voltage circuits and the digital circuits, respectively, with the ground terminals of these circuits being connected to a new negative oscillating power supply voltage VNN′. Exemplary waveforms for these oscillating power supply voltages are shown in the lower panel of the figure. Note that these oscillating power supply voltages preserve the voltage differentials VPP′ - VNN′ = VPP and VDD′ - VNN′ = VDD, where VPP is the desired amplitude of the voltage V_{LC} applied to the liquid crystal, and VDD is the power supply voltage for the digital circuitry. For the digital inputs to operate properly with these oscillating power supplies, the single-ended drive circuitry also includes voltage-shifting circuitry **1200** presenting these digital inputs as signals relative to VNN′ rather than GND.

Exemplary waveforms for a grayscale voltage adjustment scheme are depicted in **FIG. 13**. In this grayscale scheme, a first square wave voltage V_i is again applied to inner electrode **1111** of a unit cell **1110** and a second square wave voltage V_o is again applied to outer electrode **1112** of the unit cell. A desired gray level is then achieved by selecting a phase difference between the two square waves. In one approach, as shown in **FIG. 13**, the drive period is divided into a discrete set of time slices corresponding to a discrete set of phase differences between the two square waves. In the nonlimiting example of **FIG. 13**, there are eight (8) time slices, providing five (5) gray levels corresponding to phase differences of 0°, 45°, 90°, 135°, and 180°. The figure depicts two gray level examples: for a phase difference of 45°, as shown in the upper right panel of the figure, the potential applied to the liquid crystal, $V_{LC} = V_i - V_o$, is an alternating pulse train with zero DC offset and an RMS voltage of VPP/4; for a phase difference of 90°, as shown in the lower right panel of the figure, V_{LC} is an alternating pulse train with zero DC offset and an RMS

voltage of VPP/2. Thus, the gray level scheme of **FIG. 13** provides a pulse-width modulated (PWM) liquid crystal waveform with zero DC offset and an adjustable RMS voltage.

The drive circuitry of **FIG. 11B** may be used to provide the grayscale waveforms of **FIG. 13** to a plurality of unit cells. However, for a grayscale implementation, an N-bit read-in is completed during each time slice of the drive period. Thus, for an implementation with T time slices (corresponding to (T/2)+1 gray levels), the serial input data is clocked at a frequency not less than T×N×f, where f is the drive frequency (it will be appreciated that T=2 corresponds to the binary drive scheme of **FIG. 11A**).

With reference now to **FIG. 14**, an illustrative embodiment is depicted as a system block diagram. The system **1400** include a communications unit **1410** coupled by one or more feeds **1412** to an antenna unit **1420**. The communications unit **1410** might include, for example, a mobile broadband satellite transceiver, or a transmitter, receiver, or transceiver module for a radio or microwave communications system, and may incorporate data multiplexing/demultiplexing circuitry, encoder/decoder circuitry, modulator/demodulator circuitry, frequency upconverters/downconverters, filters, amplifiers, diplexes, etc. The antenna unit includes at least one surface scattering antenna, which may be configured to transmit, receive, or both; and in some approaches the antenna unit **1420** may comprise multiple surface scattering antennas, e.g. first and second surface scattering antennas respectively configured to transmit and receive. For embodiments having a surface scattering antenna with multiple feeds, the communications unit may include MIMO circuitry. The system **1400** also includes an antenna controller **1430** configured to provide control input(s) **1432** that determine the configuration of the antenna. For example, the control inputs(s) may include inputs for each of the scattering elements (e.g. for a direct addressing configuration such as depicted in **FIG. 12**), row and column inputs (e.g. for a matrix addressing configuration such as that depicted in **FIG. 13**), adjustable gains for the antenna feeds, etc.

In some approaches, the antenna controller **1430** includes circuitry configured to provide control input(s) **1432** that correspond to a selected or desired antenna

radiation pattern. For example, the antenna controller **1430** may store a set of configurations of the surface scattering antenna, e.g. as a lookup table that maps a set of desired antenna radiation patterns (corresponding to various beam directions, beams widths, polarization states, etc. as discussed earlier in this disclosure) to a corresponding set of values for the control input(s) **1432**. This lookup table may be previously computed, e.g. by performing full-wave simulations of the antenna for a range of values of the control input(s) or by placing the antenna in a test environment and measuring the antenna radiation patterns corresponding to a range of values of the control input(s). In some approaches the antenna controller may be configured to use this lookup table to calculate the control input(s) according to a regression analysis; for example, by interpolating values for the control input(s) between two antenna radiation patterns that are stored in the lookup table (e.g. to allow continuous beam steering when the lookup table only includes discrete increments of a beam steering angle). The antenna controller **1430** may alternatively be configured to dynamically calculate the control input(s) **1432** corresponding to a selected or desired antenna radiation pattern, e.g. by computing a holographic pattern corresponding to an interference term $\mathrm{Re}[\Psi_{out}\Psi_{in}^{*}]$ (as discussed earlier in this disclosure), or by computing the couplings $\{\alpha_j\}$ (corresponding to values of the control input(s)) that provide the selected or desired antenna radiation pattern in accordance with equation (1) presented earlier in this disclosure.

In some approaches the antenna unit **1420** optionally includes a sensor unit **1422** having sensor components that detect environmental conditions of the antenna (such as its position, orientation, temperature, mechanical deformation, etc.). The sensor components can include one or more GPS devices, gyroscopes, thermometers, strain gauges, etc., and the sensor unit may be coupled to the antenna controller to provide sensor data **1424** so that the control input(s) **1432** may be adjusted to compensate for translation or rotation of the antenna (e.g. if it is mounted on a mobile platform such as an aircraft) or for temperature drift, mechanical deformation, etc.

In some approaches the communications unit may provide feedback signal(s) **1434** to the antenna controller for feedback adjustment of the control input(s). For example, the communications unit may provide a bit error rate signal and the antenna

controller may include feedback circuitry (e.g. DSP circuitry) that adjusts the antenna configuration to reduce the channel noise. Alternatively or additionally, for pointing or steering applications the communications unit may provide a beacon signal (e.g. from a satellite beacon) and the antenna controller may include feedback circuitry (e.g. pointing lock DSP circuitry for a mobile broadband satellite transceiver).

An illustrative embodiment is depicted as a process flow diagram in **FIG. 15**. Flow **1500** includes operation **1510**—selecting a first antenna radiation pattern for a surface scattering antenna that is adjustable responsive to one or more control inputs. For example, an antenna radiation pattern may be selected that directs a primary beam of the radiation pattern at the location of a telecommunications satellite, a telecommunications base station, or a telecommunications mobile platform. Alternatively or additionally, an antenna radiation pattern may be selected to place nulls of the radiation pattern at desired locations, e.g. for secure communications or to remove a noise source. Alternatively or additionally, an antenna radiation pattern may be selected to provide a desired polarization state, such as circular polarization (e.g. for Ka-band satellite communications) or linear polarization (e.g. for Ku-band satellite communications). Flow **1500** includes operation **1520**—determining first values of the one or more control inputs corresponding to the first selected antenna radiation pattern. For example, in the system of **FIG. 14**, the antenna controller **1430** can include circuitry configured to determine values of the control inputs by using a lookup table, or by computing a hologram corresponding to the desired antenna radiation pattern. Flow **1500** optionally includes operation **1530**— providing the first values of the one or more control inputs for the surface scattering antenna. For example, the antenna controller **1430** can apply bias voltages to the various scattering elements, and/or the antenna controller **1430** can adjust the gains of antenna feeds. Flow **1500** optionally includes operation **1540**—selecting a second antenna radiation pattern different from the first antenna radiation pattern. Again this can include selecting, for example, a second beam direction or a second placement of nulls. In one application of this approach, a satellite communications terminal can switch between multiple satellites, e.g. to optimize capacity during peak loads, to switch to another satellite that may have entered service, or to switch from a primary satellite

that has failed or is off-line. Flow **1500** optionally includes operation **1550**—determining second values of the one or more control inputs corresponding to the second selected antenna radiation pattern. Again this can include, for example, using a lookup table or computing a holographic pattern. Flow **1500** optionally includes operation **1560**—providing the second values of the one or more control inputs for the surface scattering antenna. Again this can include, for example, applying bias voltages and/or adjusting feed gains.

Another illustrative embodiment is depicted as a process flow diagram in **FIG. 16**. Flow **1600** includes operation **1610**—identifying a first target for a first surface scattering antenna, the first surface scattering antenna having a first adjustable radiation pattern responsive to one or more first control inputs. This first target could be, for example, a telecommunications satellite, a telecommunications base station, or a telecommunications mobile platform. Flow **1600** includes operation **1620**—repeatedly adjusting the one or more first control inputs to provide a substantially continuous variation of the first adjustable radiation pattern responsive to a first relative motion between the first target and the first surface scattering antenna. For example, in the system of **FIG. 14**, the antenna controller **1430** can include circuitry configured to steer a radiation pattern of the surface scattering antenna, e.g. to track the motion of a non-geostationary satellite, to maintain pointing lock with a geostationary satellite from a mobile platform (such as an airplane or other vehicle), or to maintain pointing lock when both the target and the antenna are moving. Flow **1600** optionally includes operation **1630**—identifying a second target for a second surface scattering antenna, the second surface scattering antenna having a second adjustable radiation pattern responsive to one or more second control inputs; and flow **1600** optionally includes operation **1640**—repeatedly adjusting the one or more second control inputs to provide a substantially continuous variation of the second adjustable radiation pattern responsive to a relative motion between the second target and the second surface scattering antenna. For example, some applications may deploy both a primary antenna unit, tracking a first object (such as a first non-geostationary satellite), and a secondary or auxiliary antenna unit, tracking a second object (such as a second non-geostationary satellite). In some approaches the

auxiliary antenna unit may include a smaller-aperture antenna (tx and/or rx) primarily used to track the location of the secondary object (and optionally to secure a link to the secondary object at a reduced quality-of-service (QoS)). Flow **1600** optionally includes operation **1650**— adjusting the one or more first control inputs to place the second target substantially within the primary beam of the first adjustable radiation pattern. For example, in an application in which the first and second antennas are components of a satellite communications terminal that interacts with a constellation of non-geostationary satellites, the first or primary antenna may track a first member of the satellite constellation until the first member approaches the horizon (or the first antenna suffers appreciable scan loss), at which time a "handoff" is accomplished by switching the first antenna to track the second member of the satellite constellation (which was being tracked by the second or auxiliary antenna). Flow **1600** optionally includes operation **1660**— identifying a new target for a second surface scattering antenna different from the first and second targets; and flow **1600** optionally includes operation **1670**— adjusting the one or more second control inputs to place the new target substantially within the primary beam of the second adjustable radiation pattern. For example, after the "handoff," the secondary or auxiliary antenna can initiate a link with a third member of the satellite constellation (e.g. as it rises above the horizon).

The foregoing detailed description has set forth various embodiments of the devices and/or processes via the use of block diagrams, flowcharts, and/or examples. Insofar as such block diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such block diagrams, flowcharts, or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. In one embodiment, several portions of the subject matter described herein may be implemented via Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), digital signal processors (DSPs), or other integrated formats. However, those skilled in the art will recognize that some aspects of the embodiments disclosed herein, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer

programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of skill in the art in light of this disclosure. In addition, those skilled in the art will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as a program product in a variety of forms, and that an illustrative embodiment of the subject matter described herein applies regardless of the particular type of signal bearing medium used to actually carry out the distribution. Examples of a signal bearing medium include, but are not limited to, the following: a recordable type medium such as a floppy disk, a hard disk drive, a Compact Disc (CD), a Digital Video Disk (DVD), a digital tape, a computer memory, etc.; and a transmission type medium such as a digital and/or an analog communication medium (e.g., a fiber optic cable, a waveguide, a wired communications link, a wireless communication link, etc.).

In a general sense, those skilled in the art will recognize that the various aspects described herein which can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or any combination thereof can be viewed as being composed of various types of "electrical circuitry." Consequently, as used herein "electrical circuitry" includes, but is not limited to, electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), and/or electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment). Those having skill in the

art will recognize that the subject matter described herein may be implemented in an analog or digital fashion or some combination thereof.

All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in any Application Data Sheet, are incorporated herein by reference, to the extent not inconsistent herewith.

One skilled in the art will recognize that the herein described components (e.g., steps), devices, and objects and the discussion accompanying them are used as examples for the sake of conceptual clarity and that various configuration modifications are within the skill of those in the art. Consequently, as used herein, the specific exemplars set forth and the accompanying discussion are intended to be representative of their more general classes. In general, use of any specific exemplar herein is also intended to be representative of its class, and the non-inclusion of such specific components (e.g., steps), devices, and objects herein should not be taken as indicating that limitation is desired.

With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations are not expressly set forth herein for sake of clarity.

While particular aspects of the present subject matter described herein have been shown and described, it will be apparent to those skilled in the art that, based upon the teachings herein, changes and modifications may be made without departing from the subject matter described herein and its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as are within the true spirit and scope of the subject matter described herein. Furthermore, it is to be understood that the invention is defined by the appended claims. It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted

as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation *is* explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean *at least* the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means *at least* two recitations, or *two or more* recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., " a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., " a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of

including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

With respect to the appended claims, those skilled in the art will appreciate that recited operations therein may generally be performed in any order. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise. With respect to context, even terms like "responsive to," "related to," or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

Aspects of the subject matter described herein are set out in the following numbered clauses:

1. An antenna, comprising:
   a wave-propagating structure; and
   a plurality of subwavelength patch elements distributed along the wave-propagating structure with inter-element spacings substantially less than a free-space wavelength corresponding to an operating frequency of the antenna, where the plurality of subwavelength patch elements have a plurality of adjustable individual electromagnetic responses to a guided wave mode of the wave-propagating structure, and the plurality of adjustable individual electromagnetic responses provide an adjustable radiation field of the antenna.

2. The antenna of clause 1, wherein the operating frequency is a microwave frequency.

3. The antenna of clause 2, wherein the microwave frequency is a Ka band frequency.

4. The antenna of clause 2, wherein the microwave frequency is a Ku band frequency.

5. The antenna of clause 2, wherein the microwave frequency is a Q band frequency.

6. The antenna of clause 1, wherein the inter-element spacing is less than one-third of the free space wavelength.

7. The antenna of clause 1, wherein the inter-element spacing is less than one-fourth of the free space wavelength.

8. The antenna of clause 1, wherein the inter-element spacing is less than one-fifth of the free space wavelength.

9. The antenna of clause 1, wherein the wave-propagating structure includes one or more conducting surfaces, and the plurality of subwavelength patch elements corresponds to a plurality of conducting patches positioned at least partially above a respective plurality of irises in the one or more conducting surfaces.

10. The antenna of clause 9, wherein the one or more conducting surfaces define first and second directions parallel to the one or more conducting surfaces, the first direction being perpendicular to the second direction.

11. The antenna of clause 10, wherein the wave-propagating structure is a substantially two-dimensional wave-propagating structure.

12. The antenna of clause 11, wherein the substantially two-dimensional wave-propagating structure is a parallel plate waveguide, and the one or more conducting surfaces are an upper conductor of the parallel plate waveguide.

13. The antenna of clause 10, wherein the wave-propagating structure includes one or more substantially one-dimensional wave-propagating structures.

14. The antenna of clause 13, wherein the one or more substantially one-dimensional wave-propagating structures include one or more closed waveguides oriented along the first direction, and the one or more conducting

surfaces are one or more respective upper surfaces of the one or more closed waveguides.

15. The antenna of clause 9, wherein the irises are circular irises.

16. The antenna of clause 9, wherein the irises are rectangular irises.

17. The antenna of clause 9, wherein the irises are slit-like irises.

18. The antenna of clause 9, wherein the conducting patches are circular patches.

19. The antenna of clause 9, wherein the conducting patches are polygonal patches.

20. The antenna of clause 10, wherein the conducting patches are rectangular patches.

21. The antenna of clause 20, wherein the rectangular patches have long dimensions parallel to the first direction.

22. The antenna of clause 21, wherein the irises are rectangular irises having long dimensions parallel to the second direction.

23. The antenna of clause 22, wherein the rectangular patches have respective lower ends and upper ends along the first direction, and the rectangular irises are positioned under the lower ends of the rectangular patches.

24. The antenna of clause 1, further comprising:
a plurality of metallic structures positioned between adjacent elements of the plurality of subwavelength patch elements to reduce inter-element coupling between the adjacent elements.

25. The antenna of clause 24, wherein each of the plurality of metallic structures is a series of vias forming a colonnade.

26. The antenna of clause 9, wherein the plurality of conducting patches is configured to provide a plurality of elliptically-polarized radiation fields responsive to iris-intermediated couplings between the conducting patches and the guided wave mode.

27. The antenna of clause 26, wherein the guided wave mode defines a plurality of time-dependent H-fields at respective locations of the plurality of irises, and the time-dependent H-fields are vectors sweeping out a plurality of ellipses.

28. The antenna of clause 27, wherein the ellipses are substantially circular.

29. The antenna of clause 27, wherein the ellipses have eccentricities not greater than 1/10.

30. The antenna of clause 26, wherein the plurality of elliptically-polarized radiation fields is a plurality of left-hand elliptically-polarized radiation fields.

31. The antenna of clause 26, wherein the plurality of elliptically-polarized radiation fields is a plurality of right-hand elliptically-polarized radiation fields.

32. The antenna of clause 26, wherein the plurality of elliptically-polarized radiation fields includes a first plurality of right-hand elliptically-polarized radiation fields and a second plurality of left-hand elliptically-polarized radiation fields.

33. The antenna of clause 26, wherein the plurality of elliptically-polarized radiation fields is a plurality of circularly-polarized radiation fields.

34. The antenna of clause 26, wherein the wave-propagating structure is a rectangular waveguide, the one or more conducting surfaces are an upper conductor of the rectangular waveguide, and the plurality of irises are positioned on the upper conductor at locations intermediate between an edge of the upper conductor and a bisector of the upper conductor.

35. The antenna of clause 34, wherein the locations intermediate between the edge and the bisector are locations halfway between the edge and the bisector.

36. The antenna of clause 26, wherein:
the wave-propagating structure is a rectangular waveguide;
the one or more conducting surfaces are an upper conductor of the rectangular waveguide;
the plurality of irises includes a first plurality of irises and a second plurality of irises;
the first plurality of irises are positioned on the upper conductor at locations intermediate between a left edge of the upper conductor and a bisector of the upper conductor; and
the second plurality of irises are positioned on the upper conductor at locations intermediate between a right edge of the upper conductor and the bisector of the upper conductor

37. The antenna of clause 36, wherein the locations intermediate between the left edge and the bisector are locations halfway between the left edge and the bisector, and the locations intermediate between the right edge and the bisector are locations halfway between the right edge and the bisector.

38. The antenna of clause 9, further comprising:
a plurality of bias voltage lines configured to provide respective bias voltages between the plurality of conducting patches and the one or more conducting surfaces; and
an electrically adjustable material disposed between the plurality of conducting patches and the plurality of irises in the one or more conducting surfaces .

39. The antenna of clause 38, wherein the electrically adjustable material includes a liquid crystal material.

40. The antenna of clause 39, wherein the liquid crystal material is a nematic liquid crystal.

41. The antenna of clause 39, wherein the liquid crystal material is a dual-frequency liquid crystal.

42. The antenna of clause 39, wherein the liquid crystal material is a polymer network liquid crystal.

43. The antenna of clause 39, wherein the liquid crystal material is a polymer dispersed liquid crystal.

44. The antenna of clause 39, further comprising:
an alignment layer positioned between the liquid crystal material and the one or more conducting surfaces, the alignment layer providing microscopic grooves parallel to the one or more conducting surfaces.

45. The antenna of clause 44, wherein the one or more conducting surfaces compose at least part of an upper metal layer of a printed circuit board, and the alignment layer is a polyimide layer coating on the upper metal later.

46. The antenna of clause 39, further comprising:
an alignment layer positioned between the liquid crystal material and the plurality of conducting patches, the alignment layer providing microscopic grooves parallel to the plurality of conducting patches.

47. The antenna of clause 46, where the plurality of conducting patches compose at least part of a lower metal layer of a printed circuit board, and the alignment layer is a polyimide coating on the lower metal layer.

48. The antenna of clause 39, wherein the electrically adjustable material includes an interstitial medium that embeds the liquid crystal material.

49. The antenna of clause 48, wherein the interstitial medium is a microporous interstitial medium.

50. The antenna of clause 49, wherein the microporous interstitial medium is ultra-high molecular weight polyethylene (UHMW-PE).

51. The antenna of clause 49, wherein the microporous interstitial medium is hydrophilic expanded polytetrafluoroethylene (hydrophilic ePTFE).

52. The antenna of clause 48, wherein the interstitial medium provides microscopic pores for surface alignment of the liquid crystal material, the microscopic pores having long dimensions that are parallel to the one or more conducting surfaces.

53. A method, comprising:

propagating a first guided wave to deliver a first plurality of relative phases to a respective plurality of locations;

coupling to the first guided wave at a first set of locations selected from the respective plurality of locations to radiate a first plurality of elliptically-polarized waves from the first set of locations, the first plurality of elliptically-polarized waves producing a first radiation field;

propagating a second guided wave to deliver a second plurality of relative phases to the respective plurality of locations, where the second plurality of relative phases is substantially equal to the first plurality of relative phases; and

coupling to the second guided wave at a second set of locations selected from the respective plurality of locations to radiate a second plurality of elliptically-polarized waves from the second set of locations, the second plurality of elliptically-polarized waves producing a second radiation field different from the first radiation field.

54. The method of clause 53, wherein:

the first guided wave and the first radiation field define a first interference pattern, and the first set of locations selected from the respective

plurality of locations corresponds to a set of locations within constructive interference regions of the first interference pattern; and

the second guided wave and the second radiation field define a second interference pattern different from the first interference pattern, and the second set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the second interference pattern.

55. The method of clause 53, wherein the first plurality of elliptically-polarized waves is a first plurality of circularly-polarized waves.

56. The method of clause 53, wherein the first plurality of elliptically-polarized waves is a first plurality of left-hand elliptically polarized waves.

57. The method of clause 53, wherein the first plurality of elliptically-polarized waves is a first plurality of right-hand elliptically polarized waves.

58. The method of clause 57, further comprising:

propagating a third guided wave to deliver a third plurality of relative phases to the respective plurality of locations, a propagation direction of the third guided wave being opposite to a propagation direction of the first guided wave; and

coupling to the third guided wave at a third set of locations selected from the respective plurality of locations to radiate a plurality of left-hand elliptically-polarized waves from the third set of locations.

59. The method of clause 58, wherein the third set of locations is equal to the first set of locations.

60. A method, comprising:

receiving a first elliptically-polarized free-space wave at a plurality of locations;

coupling to the first elliptically-polarized free-space wave at a first set of locations selected from the plurality of locations to produce a first

plurality of electromagnetic oscillations at the first set of locations, the first plurality of electromagnetic oscillations producing a first guided wave having a first plurality of relative phases at the plurality of locations;

receiving a second elliptically-polarized free-space wave different from the first elliptically-polarized free-space wave at the plurality of locations;

coupling to the second elliptically-polarized free-space wave at a second set of locations selected from the plurality of locations to produce a second plurality of electromagnetic oscillations at the second set of locations, the second plurality of electromagnetic oscillations producing a second guided wave having a second plurality of relative phases at the plurality of locations, where the second plurality of relative phases is substantially equal to the first plurality of relative phases.

61. The method of clause 60, wherein:

the first guided wave and the first elliptically-polarized free-space wave define a first interference pattern, and the first set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the first interference pattern; and

the second guided wave and the second elliptically-polarized free-space wave define a second interference pattern different from the first interference pattern, and the second set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the second interference pattern.

62. The method of clause 60, wherein the first elliptically-polarized free-space wave is a circularly-polarized free-space wave.

63. The method of clause 60, wherein the first elliptically-polarized free-space wave is a left-hand elliptically-polarized free-space wave.

64. The method of clause 60, wherein the first elliptically-polarized free-space wave is a right-hand elliptically-polarized free-space wave.

65. The method of clause 64, further comprising:

receiving a left-hand elliptically-polarized free-space wave at the plurality of locations;

coupling to the right-hand elliptically-polarized free-space wave at a third set of locations selected from the plurality of locations to produce a third plurality of electromagnetic oscillations at the third set of locations, the third plurality of electromagnetic oscillations producing a third guided wave, a propagation direction of the third guided wave being opposite to a propagation direction of the first guided wave.

66. The method of clause 65, wherein the third set of locations is equal to the first set of locations.

67. An antenna, comprising:

a wave-propagating structure;

a plurality of radiating elements distributed along the wave-propagating structure with inter-element spacings substantially less than a free-space wavelength corresponding to an operating frequency of the antenna, where the plurality of radiating elements are configured to provide a plurality of adjustable linearly-polarized radiation fields responsive to a guided wave mode of the wave-propagating structure; and

a polarization conversion structure having an input surface and an output surface and configured to receive the plurality of adjustable linearly-polarized radiation fields at the input surface and transmit a corresponding plurality of adjustable elliptically-polarized radiation fields from the output surface;

where the plurality of adjustable elliptically-polarized radiation fields provide an adjustable elliptically-polarized radiation field of the antenna.

68. The antenna of clause 67, where the polarization conversion structure is a quarter-wave plate.

69. The antenna of clause 67, where the polarization conversion structure is an anisotropic dielectric material.

70. The antenna of clause 67, wherein the polarization conversion structure is an artificial magnetic material.

71. The antenna of clause 67, wherein the polarization conversion structure is a meander-line structure.

72. The antenna of clause 71, wherein the meander-line structure is a multilayered structure including two or more conducting meander line arrays with interleaved spacer layers.

73. The antenna of clause 71, wherein the meander-line structure includes three-dimensional meander lines.

74. The antenna of clause 67, wherein the adjustable elliptically-polarized radiation field is a substantially circularly-polarized radiation field.

75. The antenna of clause 67, wherein an axial ratio of the adjustable elliptically-polarized radiation field is less than 2 dB for directions within a cone of half-angle 50° centered on a broadside axis of the antenna.

76. An electromagnetic apparatus, comprising:
a wave-propagating structure;
a plurality of resonant elements distributed along a conducting surface of the wave-propagating structure; and
a liquid crystal material disposed proximate to the plurality of resonant elements;
wherein each resonant element includes a first electrode and a second electrode, the first electrode being configured to align the liquid crystal substantially parallel to electric field lines of a resonance mode of the

resonant element, and the second electrode being configured to align the liquid crystal substantially perpendicular to the electric field lines of the resonance mode.

77. The electromagnetic apparatus of clause 76, wherein the plurality of second electrodes compose a common electrode that extends between the plurality of resonant elements.

78. The electromagnetic apparatus of clause 77, wherein the plurality of first electrodes is a plurality of conducting islands substantially coplanar with and electrically disconnected from the conducting surface, the liquid crystal is disposed in a layer above the conducting surface, and the plurality of second electrodes compose a conducting layer above the liquid crystal layer, the conducting layer being substantially transparent to the resonance modes.

79. The electromagnetic apparatus of clause 78, wherein the plurality of resonant elements is a plurality of complementary electric LC (CELC) resonators defined by the plurality of conducting islands and the conducting surface.

80. The electromagnetic apparatus of clause 78, wherein the conducting layer is a chromium or titanium layer having a thickness of less than 30 nanometers.

81. The electromagnetic apparatus of clause 78, wherein the conducting layer is an organic conductor.

82. The electromagnetic apparatus of clause 78, wherein the conducting layer is an anisotropic conducting layer with a first conductivity in a first direction and a second conductivity in a second direction, the second conductivity being less than the first conductivity, and the first direction is substantially perpendicular to the electric field lines of the resonance modes.

83. The electromagnetic apparatus of clause 76, wherein the plurality of first electrodes is a plurality of conducting patches positioned above a respective plurality of irises in the conducting surface, the liquid crystal is disposed in a

layer between the conducting surface and the plurality of conducting patches, and the plurality of second electrodes is substantially coplanar with and electrically disconnected from the conducting patches, the plurality of second electrodes being substantially transparent to the resonance modes.

84. A method of tuning an electromagnetic resonator with a proximate liquid crystal, the method comprising:
first aligning the liquid crystal substantially parallel to electric field lines of a resonance mode of the electromagnetic resonator; and
second aligning the liquid crystal substantially perpendicular to the electric field lines of the resonance mode.

85. The method of clause 84, wherein the electromagnetic resonator includes a conducting island substantially coplanar with and electrically disconnected from the conducting surface, and the first aligning includes applying a voltage difference V1 between the conducting island and the conducting surface.

86. The method of clause 85, wherein V1 is an AC voltage difference having substantially zero DC offset.

87. The method of clause 86, wherein an AC frequency range of V1 is between 10 Hz and 100 kHz.

88. The method of clause 86, wherein an RMS value of V1 is greater than a saturation RMS voltage of the liquid crystal.

89. The method of clause 86, wherein the electromagnetic resonator further includes a counter-electrode above the conducting island and the conducting surface, and the second aligning includes applying a voltage difference V2 between the counter-electrode and the conducting surface substantially greater than the voltage difference V1 between the conducting island and the conducting surface.

90. The method of clause 89, wherein V2 is an AC voltage difference having substantially zero DC offset.

91. The method of clause 90, wherein an AC frequency range of V2 is between 10 Hz and 100 kHz.

92. The method of clause 90, wherein an RMS value of V2 is greater than a saturation RMS voltage of the liquid crystal.

93. The method of clause 90, wherein V1 is substantially zero during the applying of the voltage difference V2.

94. The method of clause 84, wherein the electromagnetic resonator includes a conducting patch positioned above an iris in a conducting surface, and the first aligning includes applying a voltage difference V1 between the conducting patch and the conducting surface.

95. The method of clause 94, wherein V1 is an AC voltage difference having substantially zero DC offset.

96. The method of clause 95, wherein an RMS value of V1 is greater than a saturation RMS voltage of the liquid crystal.

97. The method of clause 95, wherein the electromagnetic resonator further includes a counter-electrode adjacent to and coplanar with the conducting patch, and the second aligning includes applying a voltage difference V2 between the counter-electrode and the conducting patch substantially greater than the voltage difference V1 between the conducting patch and the conducting surface.

98. The method of clause 97, wherein V2 is an AC voltage difference having substantially zero DC offset.

99. The method of clause 98, wherein an RMS value of V2 is greater than a saturation RMS voltage of the liquid crystal.

100. The method of clause 98, wherein V1 is substantially zero during the applying of the voltage difference V2.

101. The method of clause 89, wherein the applying of the voltage difference V2 is an applying for a duration less than a relaxation time of the liquid crystal.

102. The method of clause 101, wherein the duration is less than half the relaxation time.

103. The method of clause 95, wherein the applying of the voltage difference V2 is an applying for a duration less than a relaxation time of the liquid crystal.

104. The method of clause 103, wherein the duration is less than half the relaxation time.

105. A method for controlling a surface scattering antenna having a plurality of scattering elements with respective tuning electrodes and a common base electrode, the method comprising, for each scattering element:
applying a first voltage difference between the tuning electrode and the common base electrode; and
applying a second voltage difference between the tuning electrode and the common base electrode;
where each voltage difference is an AC voltage difference having substantially zero DC offset.

106. The method of clause 105, wherein the first voltage difference has an RMS value equal a first fraction times VPP and the second voltage difference has an RMS value equal to a second fraction times VPP, where VPP is a voltage greater than a saturation RMS voltage of a liquid crystal disposed intermediate the tuning electrode and the common base electrode.

107. The method of clause 106, wherein the applying of the first voltage difference includes:

applying a first square wave alternating between VPP and ground (GND) to the tuning electrode; and

applying a second square wave alternating between VPP and GND to the common base electrode;

where the first square wave and the second square wave have a phase difference equal to the first fraction times 180 degrees.

108. The method of clause 106, wherein the applying of the second voltage difference includes:

applying a first square wave alternating between VPP and ground (GND) to the tuning electrode; and

applying a second square wave alternating between VPP and GND to the common base electrode;

where the first square wave and the second square wave have a phase difference equal to the second fraction times 180 degrees.

109. The method of clause 106, wherein the first fraction is equal to one.

110. The method of clause 109, wherein the applying of the first voltage difference includes:

applying a first square alternating between VPP and –VPP to the tuning electrode; and

grounding the common base electrode.

111. The method of clause 106, wherein the second fraction is equal to zero.

112. The method of clause 111, wherein the applying of the second voltage difference includes:

grounding both the tuning electrode and the common base electrode.

113. A driver for a surface scattering antenna having a plurality of scattering elements with respective tuning electrodes and a common base electrode, the driver comprising:

a serial shift register configured to read in a sequence of bits;

a latch configured to store the sequence of bits in a parallel register; and

a set of push-pull amplifiers configured to drive the plurality of tuning electrodes with voltages corresponding to a respective plurality of bits selected from the parallel register.

114. The driver of clause 113, wherein the set of push-pull amplifiers is further configured to drive the common base electrode with a voltage corresponding to another bit selected from the parallel register.

115. The driver of clause 113, further comprising:

a parallel xor gate configured to invert the output of the parallel register responsive to a polarity signal.

116. The driver of clause 113, wherein positive terminals of the push-pull amplifiers are connected to a voltage VPP and negative terminals of the push-pull amplifiers are connected to ground (GND), VPP being defined as a voltage greater than a saturation RMS voltage of a liquid crystal disposed intermediate the tuning electrodes and the common base electrode.

117. The driver of clause 113, further comprising:

positive power circuitry configured to drive positive terminals of the push-pull amplifiers with a first square wave alternating between VPP and GND; and

negative power circuitry configured to drive negative terminals of the push-pull amplifiers with a second square wave alternating between GND and –VPP in phase with the first square wave;

where VPP is a voltage greater than a saturation RMS voltage of a liquid crystal disposed intermediate the tuning electrodes and the common base electrode.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not

intended to be limiting, with the true scope and spirit being indicated by the following claims.

CLAIMS

1. An antenna, comprising:

a wave-propagating structure; and

a plurality of subwavelength patch elements distributed along the wave-propagating structure with inter-element spacings substantially less than a free-space wavelength corresponding to an operating frequency of the antenna, where the plurality of subwavelength patch elements have a plurality of adjustable individual electromagnetic responses to a guided wave mode of the wave-propagating structure, and the plurality of adjustable individual electromagnetic responses provide an adjustable radiation field of the antenna.

2. The antenna of claim 1, wherein the operating frequency is a microwave frequency.

3. The antenna of claim 1, wherein the wave-propagating structure includes one or more conducting surfaces, and the plurality of subwavelength patch elements corresponds to a plurality of conducting patches positioned at least partially above a respective plurality of irises in the one or more conducting surfaces.

4. The antenna of claim 3, wherein the one or more conducting surfaces define first and second directions parallel to the one or more conducting surfaces, the first direction being perpendicular to the second direction.

5. The antenna of claim 4, wherein the wave-propagating structure is a substantially two-dimensional wave-propagating structure.

6. The antenna of claim 5, wherein the substantially two-dimensional wave-propagating structure is a parallel plate waveguide, and the one or more conducting surfaces are an upper conductor of the parallel plate waveguide.

7. The antenna of claim 4, wherein the wave-propagating structure includes one or more substantially one-dimensional wave-propagating structures.

8. The antenna of claim 7, wherein the one or more substantially one-dimensional wave-propagating structures include one or more closed waveguides oriented along the first direction, and the one or more conducting surfaces are one or more respective upper surfaces of the one or more closed waveguides.

9. The antenna of claim 3, wherein the plurality of conducting patches is configured to provide a plurality of elliptically-polarized radiation fields responsive to iris-intermediated couplings between the conducting patches and the guided wave mode.

10. The antenna of claim 9, wherein the guided wave mode defines a plurality of time-dependent H-fields at respective locations of the plurality of irises, and the time-dependent H-fields are vectors sweeping out a plurality of ellipses.

11. The antenna of claim 10, wherein the ellipses are substantially circular.

12. A method, comprising:

propagating a first guided wave to deliver a first plurality of relative phases to a respective plurality of locations;

coupling to the first guided wave at a first set of locations selected from the respective plurality of locations to radiate a first plurality of elliptically-polarized waves from the first set of locations, the first plurality of elliptically-polarized waves producing a first radiation field;

propagating a second guided wave to deliver a second plurality of relative phases to the respective plurality of locations, where the second plurality of relative phases is substantially equal to the first plurality of relative phases; and

coupling to the second guided wave at a second set of locations selected from the respective plurality of locations to radiate a second plurality of elliptically-polarized waves from the second set of locations, the second plurality of elliptically-polarized waves producing a second radiation field different from the first radiation field.

13. The method of claim 12, wherein:

the first guided wave and the first radiation field define a first interference pattern, and the first set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the first interference pattern; and

the second guided wave and the second radiation field define a second interference pattern different from the first interference pattern, and the second set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the second interference pattern.

14. The method of claim 12, wherein the first plurality of elliptically-polarized waves is a first plurality of circularly-polarized waves.

15. The method of claim 12, wherein the first plurality of elliptically-polarized waves is a first plurality of left-hand elliptically polarized waves.

16. The method of claim 12, wherein the first plurality of elliptically-polarized waves is a first plurality of right-hand elliptically polarized waves.

17. The method of claim 16, further comprising:

propagating a third guided wave to deliver a third plurality of relative phases to the respective plurality of locations, a propagation direction of the third guided wave being opposite to a propagation direction of the first guided wave; and

coupling to the third guided wave at a third set of locations selected from the respective plurality of locations to radiate a plurality of left-hand elliptically-polarized waves from the third set of locations.

18. The method of claim 17, wherein the third set of locations is equal to the first set of locations.

19. A method, comprising:

receiving a first elliptically-polarized free-space wave at a plurality of locations;

coupling to the first elliptically-polarized free-space wave at a first set of locations selected from the plurality of locations to produce a first plurality of electromagnetic oscillations at the first set of locations, the first plurality of electromagnetic oscillations producing a first guided wave having a first plurality of relative phases at the plurality of locations;

receiving a second elliptically-polarized free-space wave different from the first elliptically-polarized free-space wave at the plurality of locations;

coupling to the second elliptically-polarized free-space wave at a second set of locations selected from the plurality of locations to produce a second plurality of electromagnetic oscillations at the second set of locations, the second plurality of electromagnetic oscillations producing a second guided wave having a second plurality of relative phases at the plurality of locations, where the second plurality of relative phases is substantially equal to the first plurality of relative phases.

20. The method of claim 19, wherein:

the first guided wave and the first elliptically-polarized free-space wave define a first interference pattern, and the first set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the first interference pattern; and

the second guided wave and the second elliptically-polarized free-space wave define a second interference pattern different from the first interference pattern, and the second set of locations selected from the respective plurality of locations corresponds to a set of locations within constructive interference regions of the second interference pattern.

21. The method of claim 19, wherein the first elliptically-polarized free-space wave is a circularly-polarized free-space wave.

22. The method of claim 19, wherein the first elliptically-polarized free-space wave is a left-hand elliptically-polarized free-space wave.

23. The method of claim 19, wherein the first elliptically-polarized free-space wave is a right-hand elliptically-polarized free-space wave.

24. The method of claim 23, further comprising:

receiving a left-hand elliptically-polarized free-space wave at the plurality of locations;

coupling to the right-hand elliptically-polarized free-space wave at a third set of locations selected from the plurality of locations to produce a third plurality of electromagnetic oscillations at the third set of locations, the third plurality of electromagnetic oscillations producing a third guided wave, a propagation direction of the third guided wave being opposite to a propagation direction of the first guided wave.

25. The method of claim 24, wherein the third set of locations is equal to the first set of locations.

FIG. 1

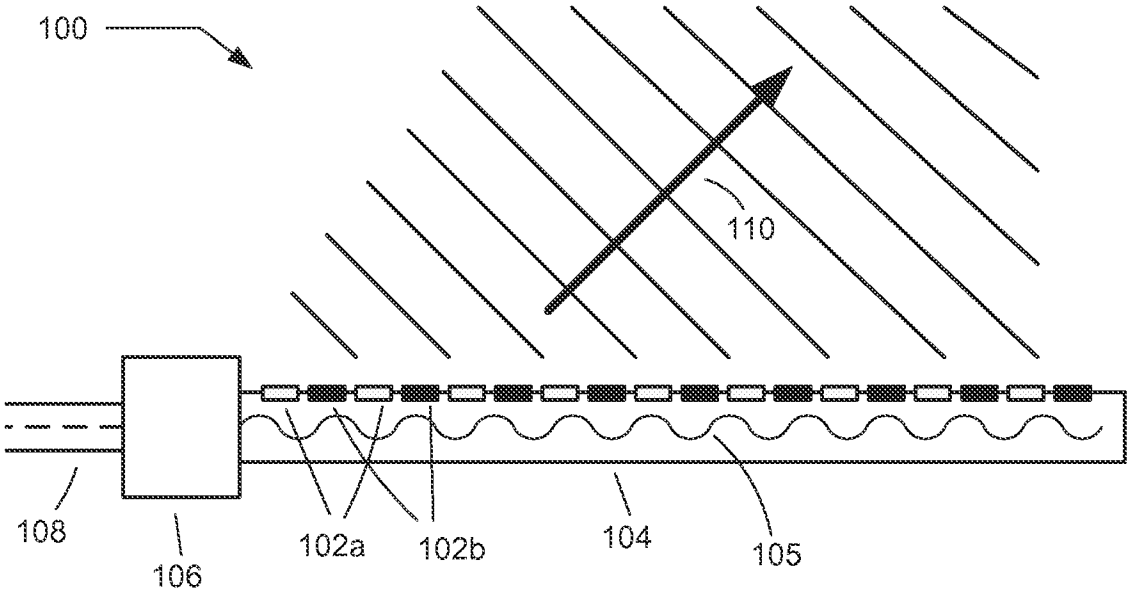


FIG. 2A

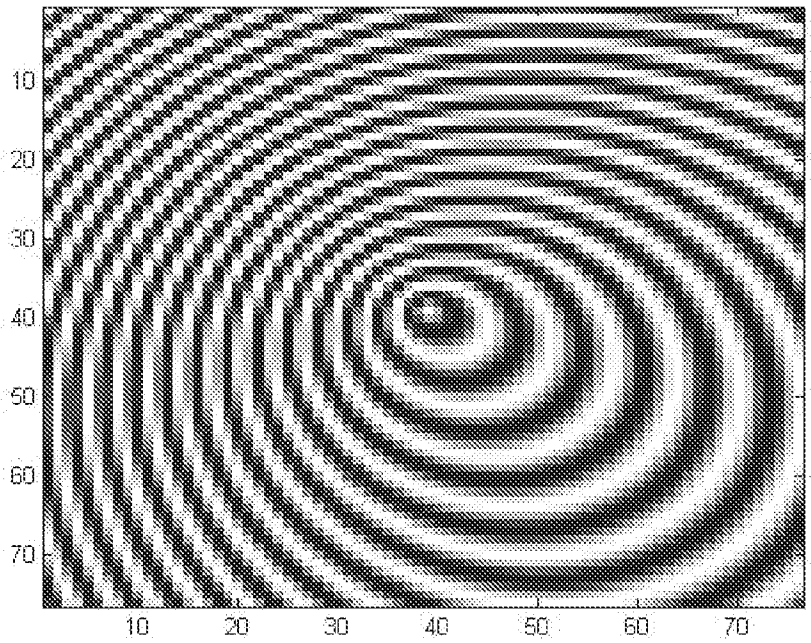


FIG. 2B

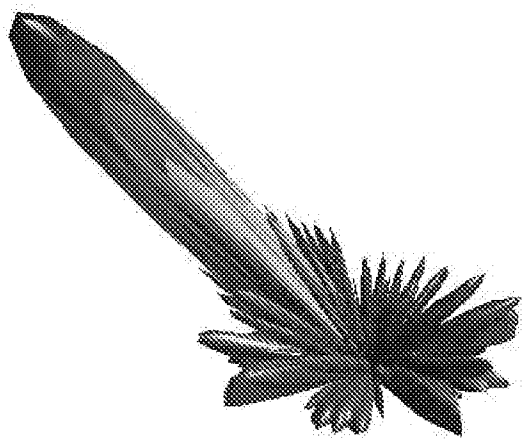


FIG. 3A

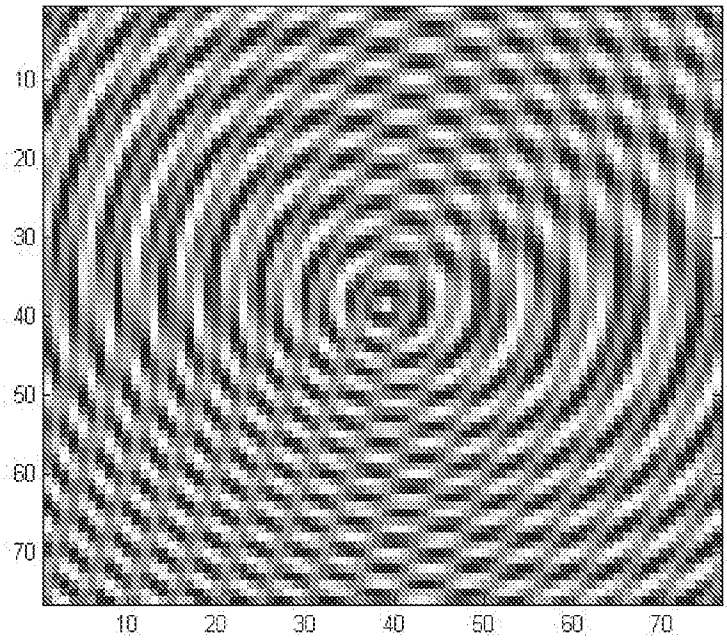


FIG. 3B

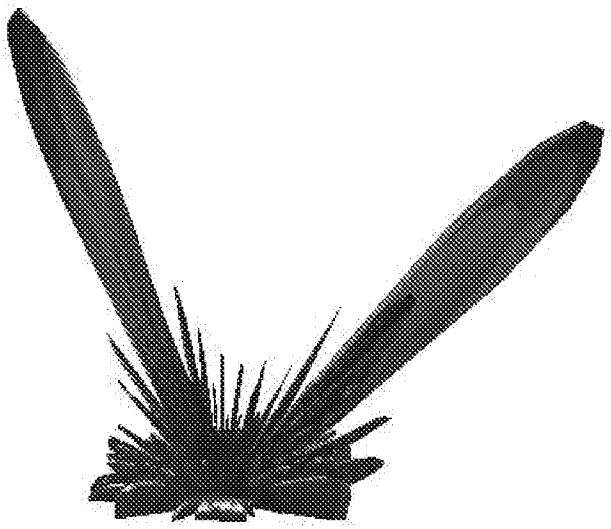


FIG. 4A

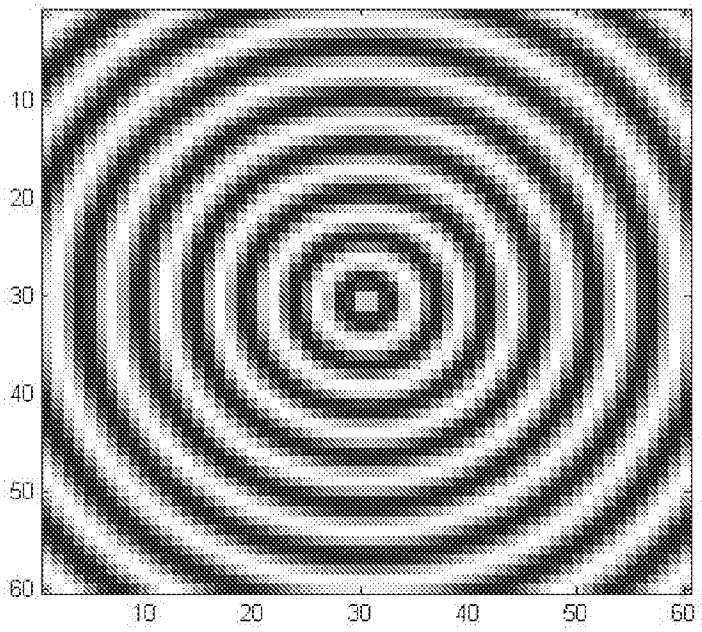


FIG. 4B

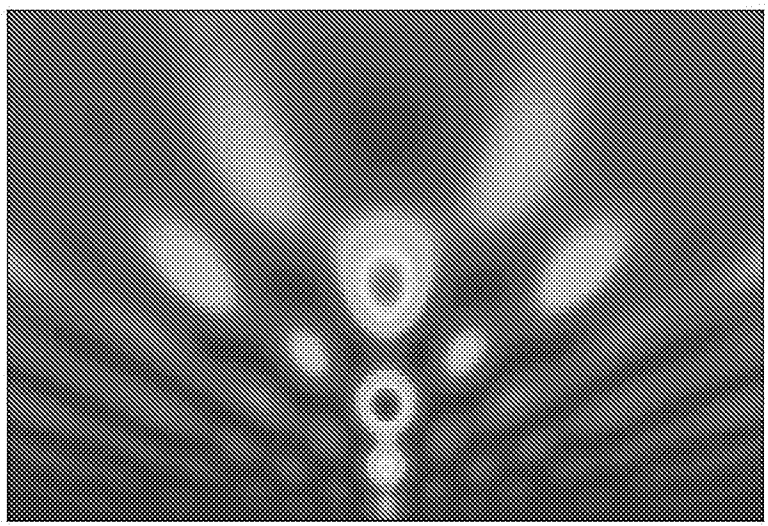


FIG. 5

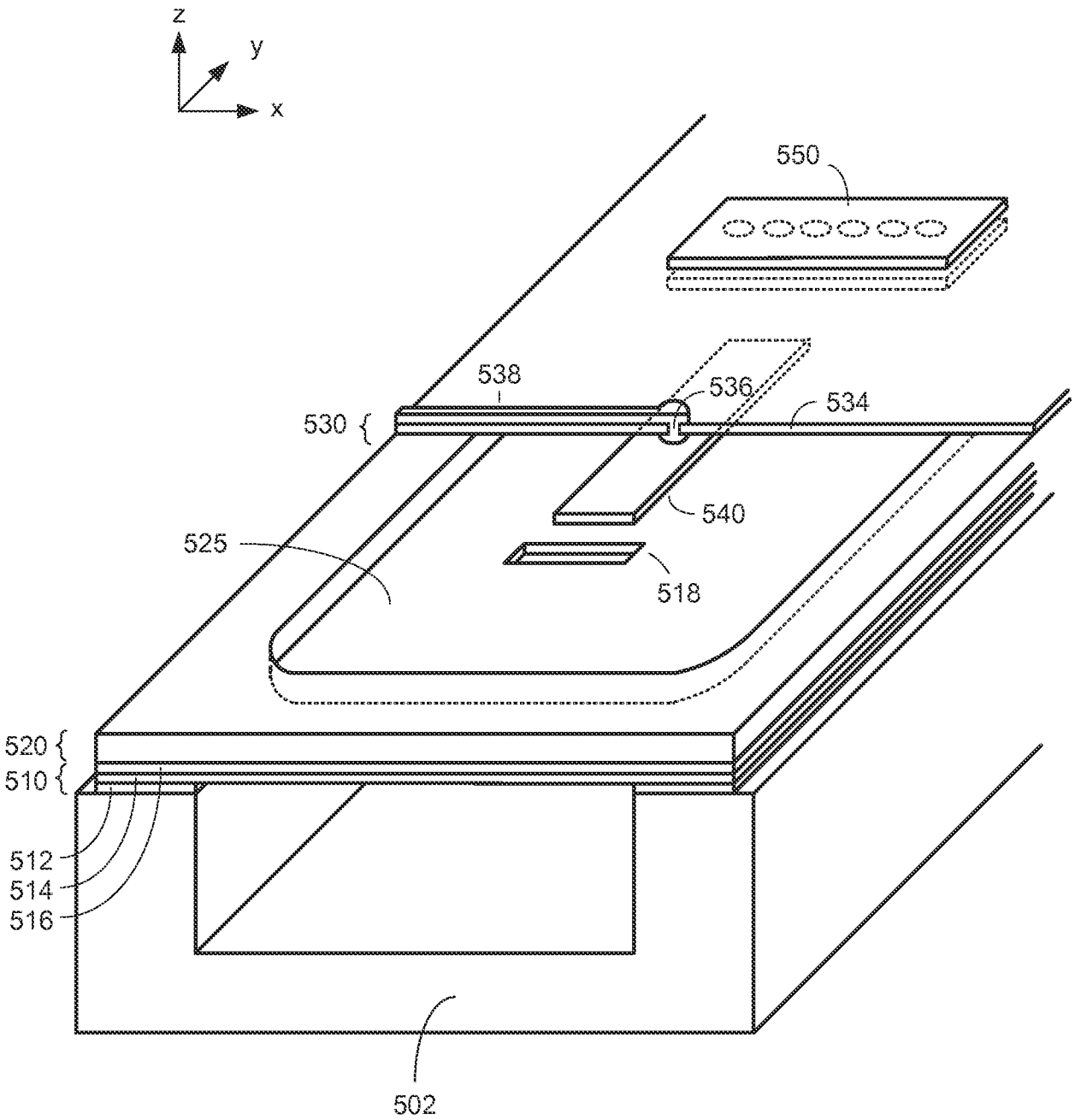


FIG. 6A

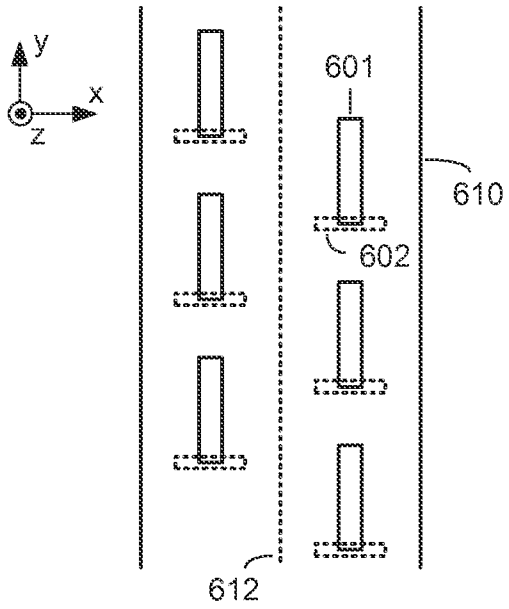


FIG. 6B

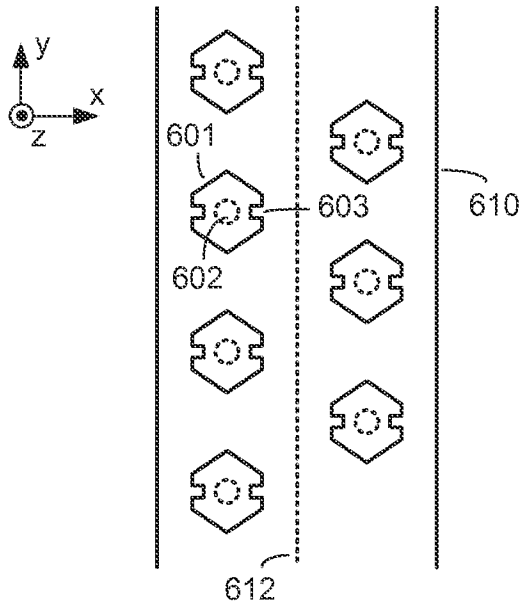


FIG. 6C

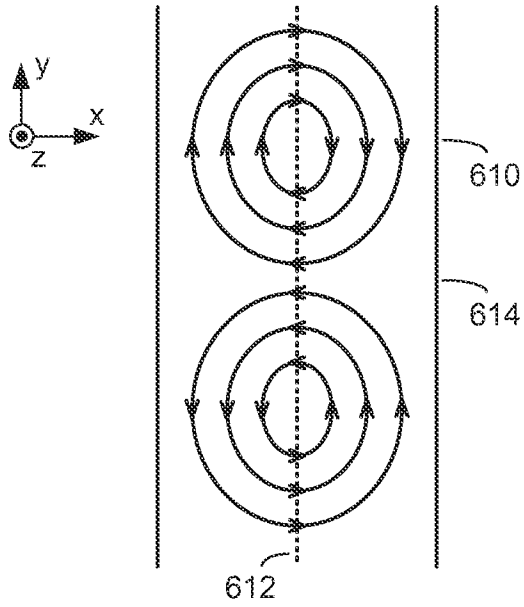


FIG. 7

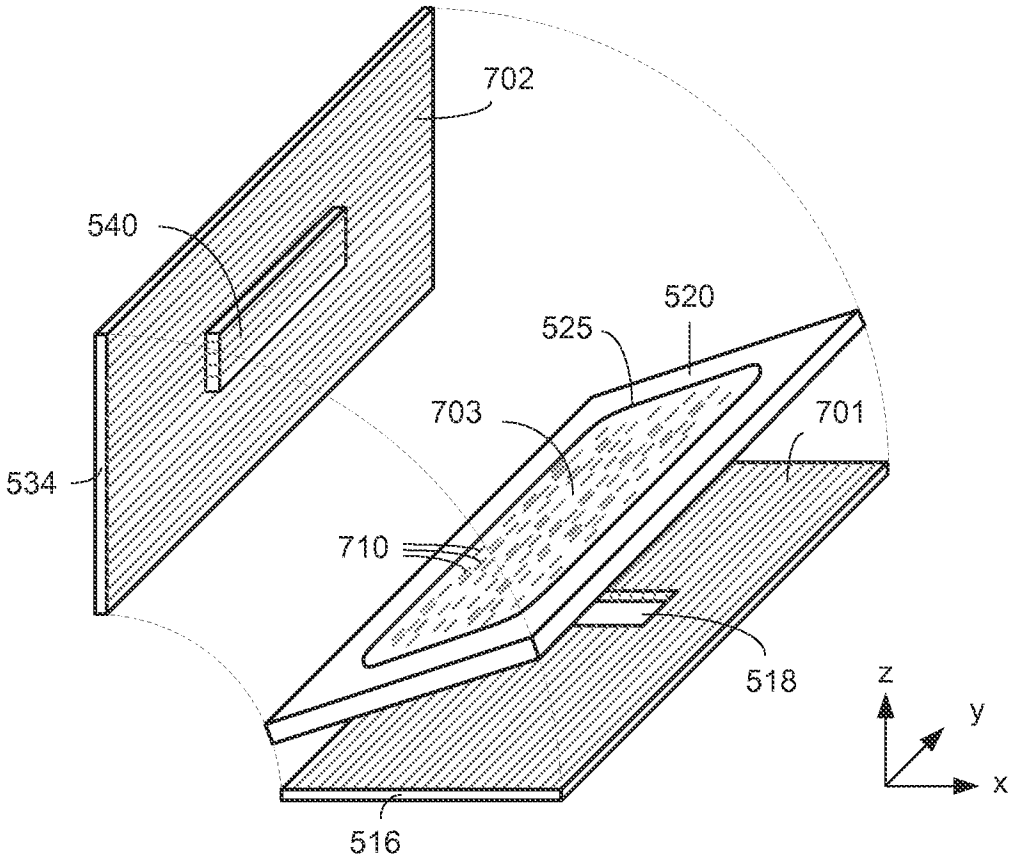


FIG. 8A

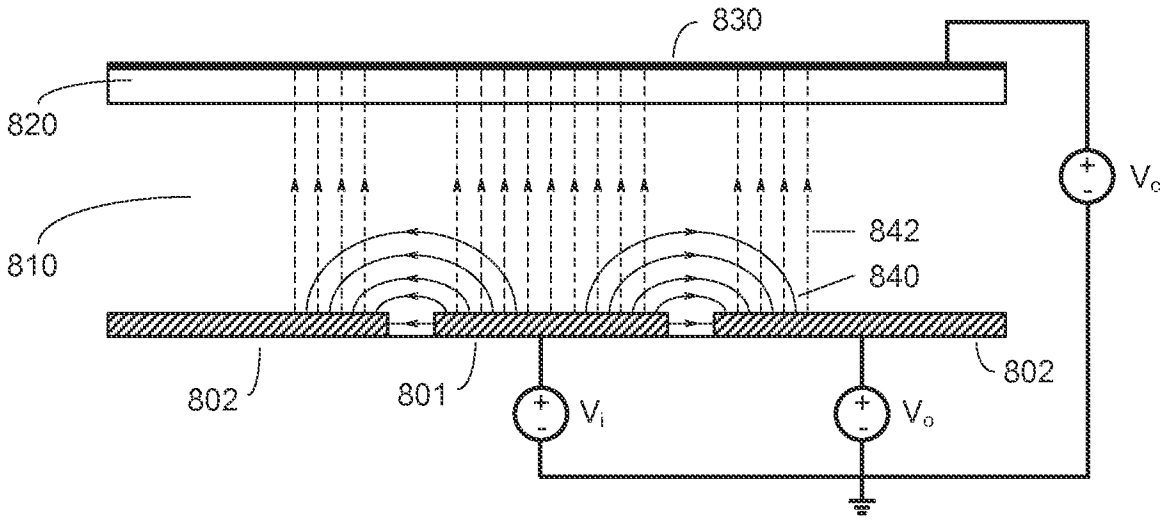

830
820
810
842
840
802
801
802
V_c
V_i
V_o

FIG. 8B

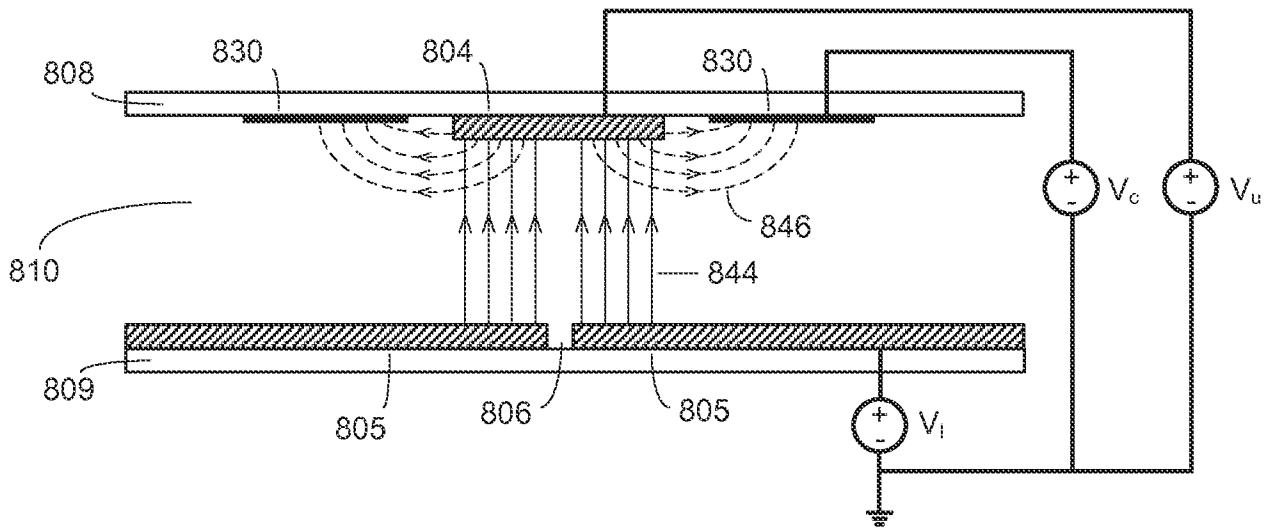

808
830
804
830
810
846
844
809
805
806
805
V_c
V_u
V_i

FIG. 9

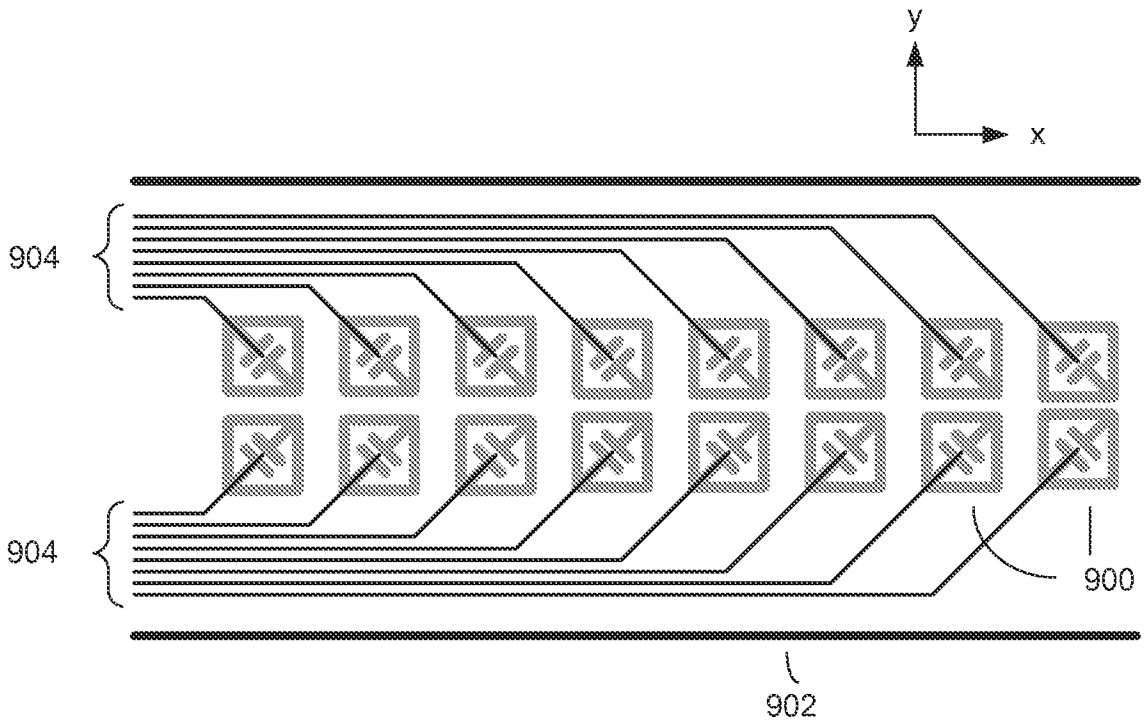
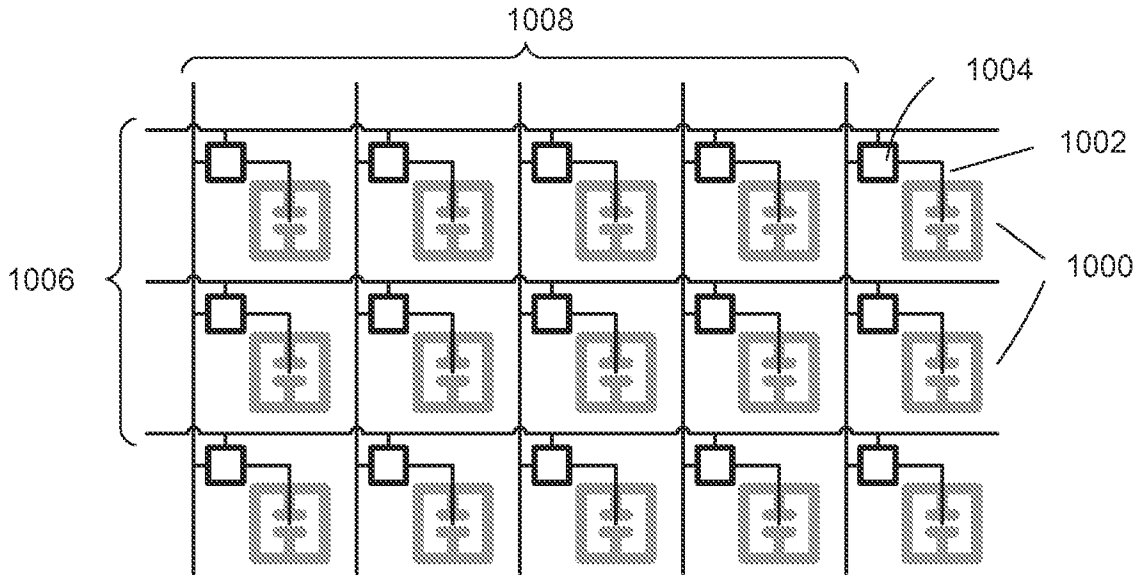


FIG. 10



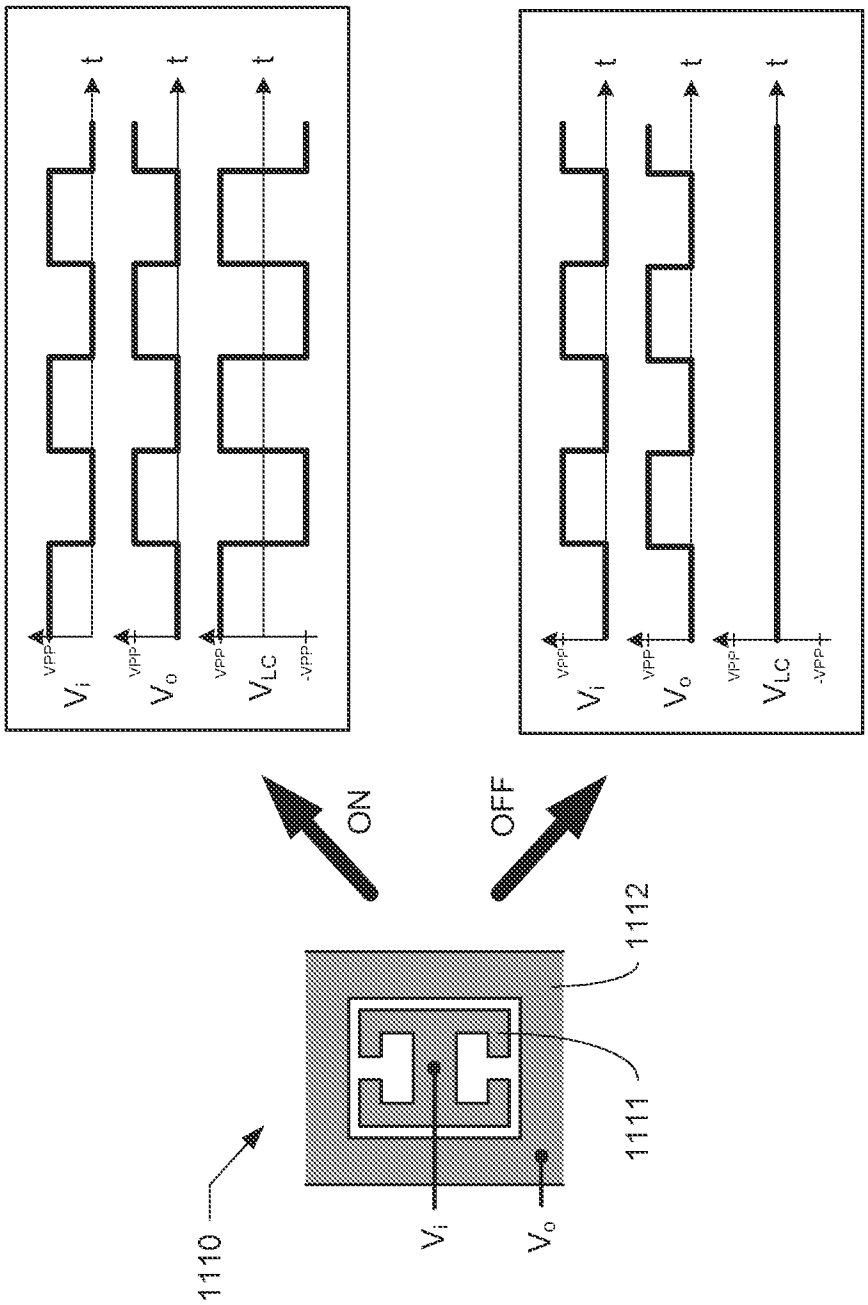
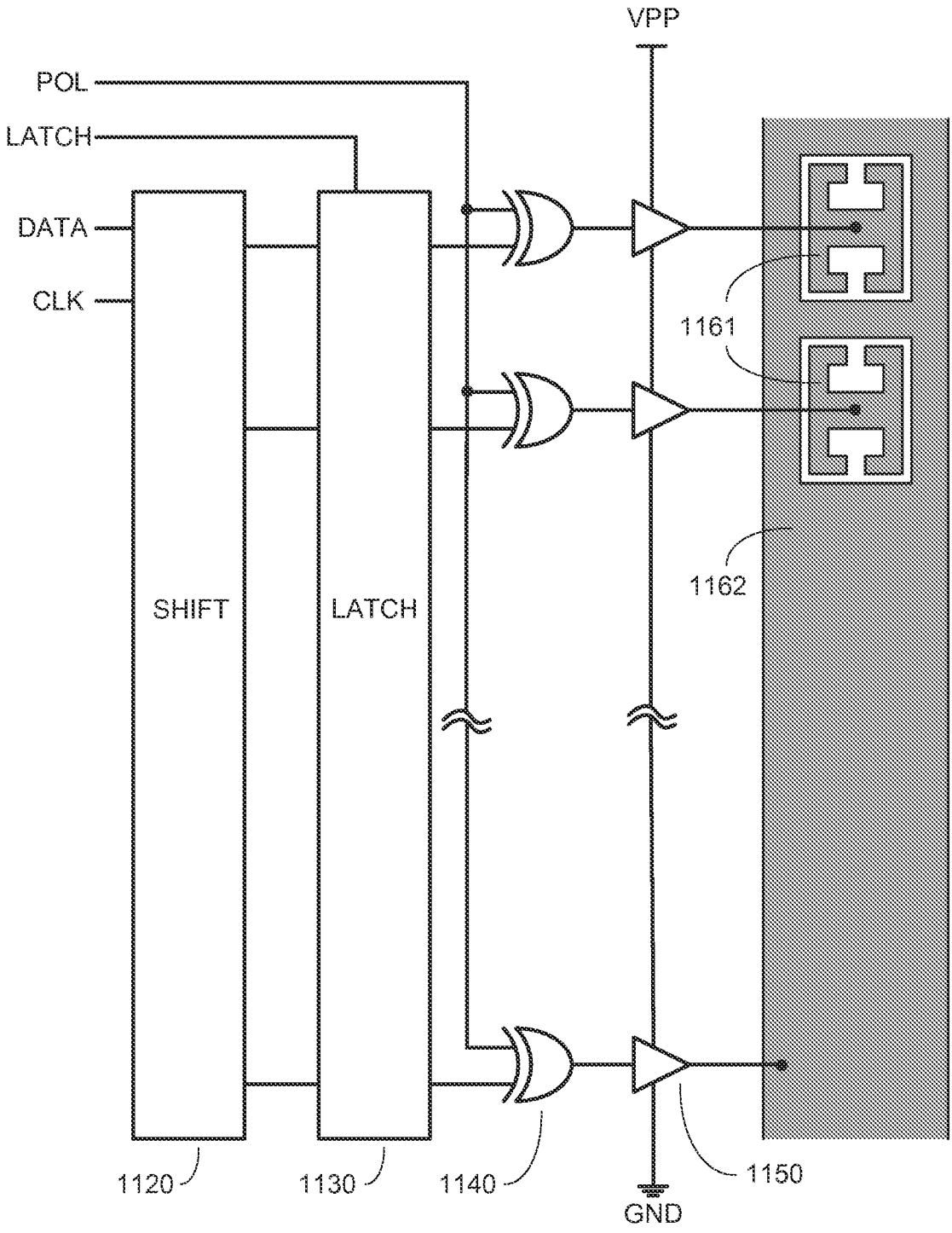


FIG. 11A

FIG. 11B


VPP
POL
LATCH
DATA
CLK
1161
1162
SHIFT
LATCH
1120
1130
1140
1150
GND

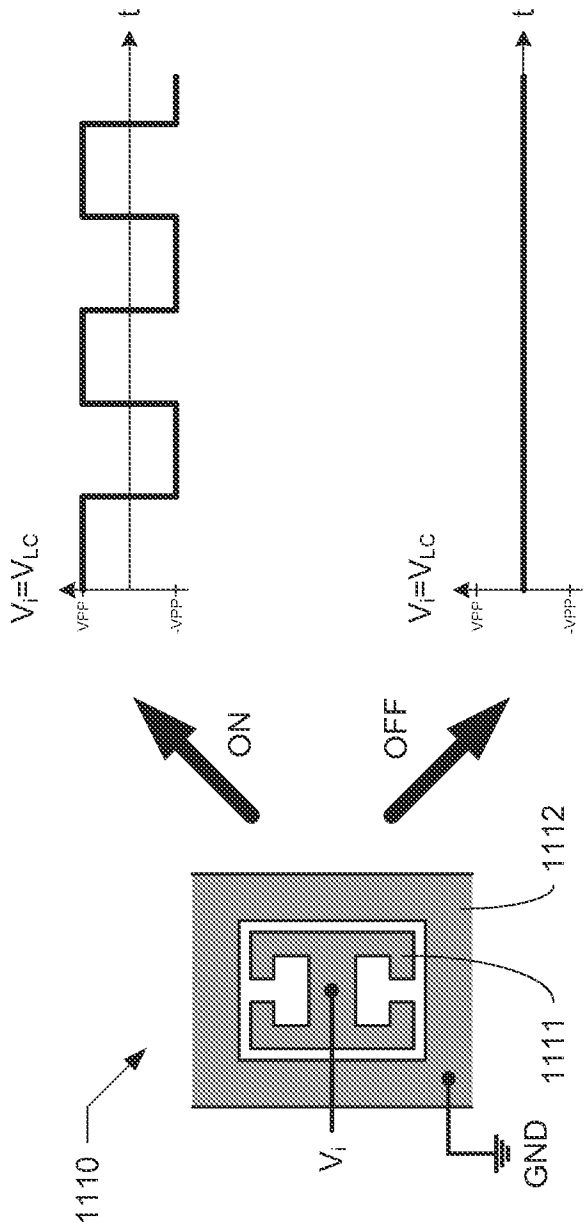
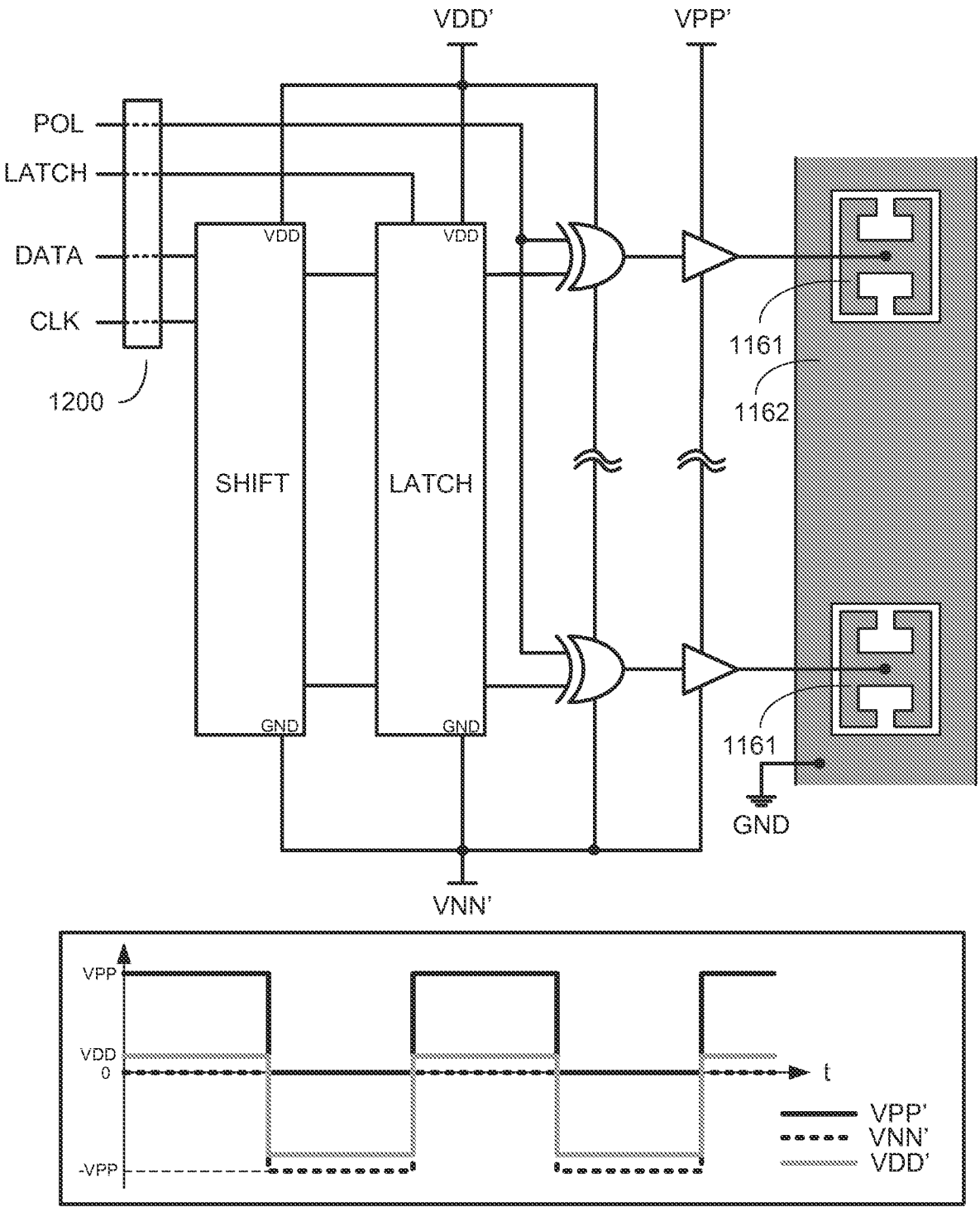


FIG. 12A

FIG. 12B


VDD'
VPP'
POL
LATCH
DATA
CLK
1200
VDD
VDD
SHIFT
LATCH
GND
GND
1161
1162
1161
GND
VNN'
VPP
VDD
0
-VPP
t
VPP'
VNN'
VDD'

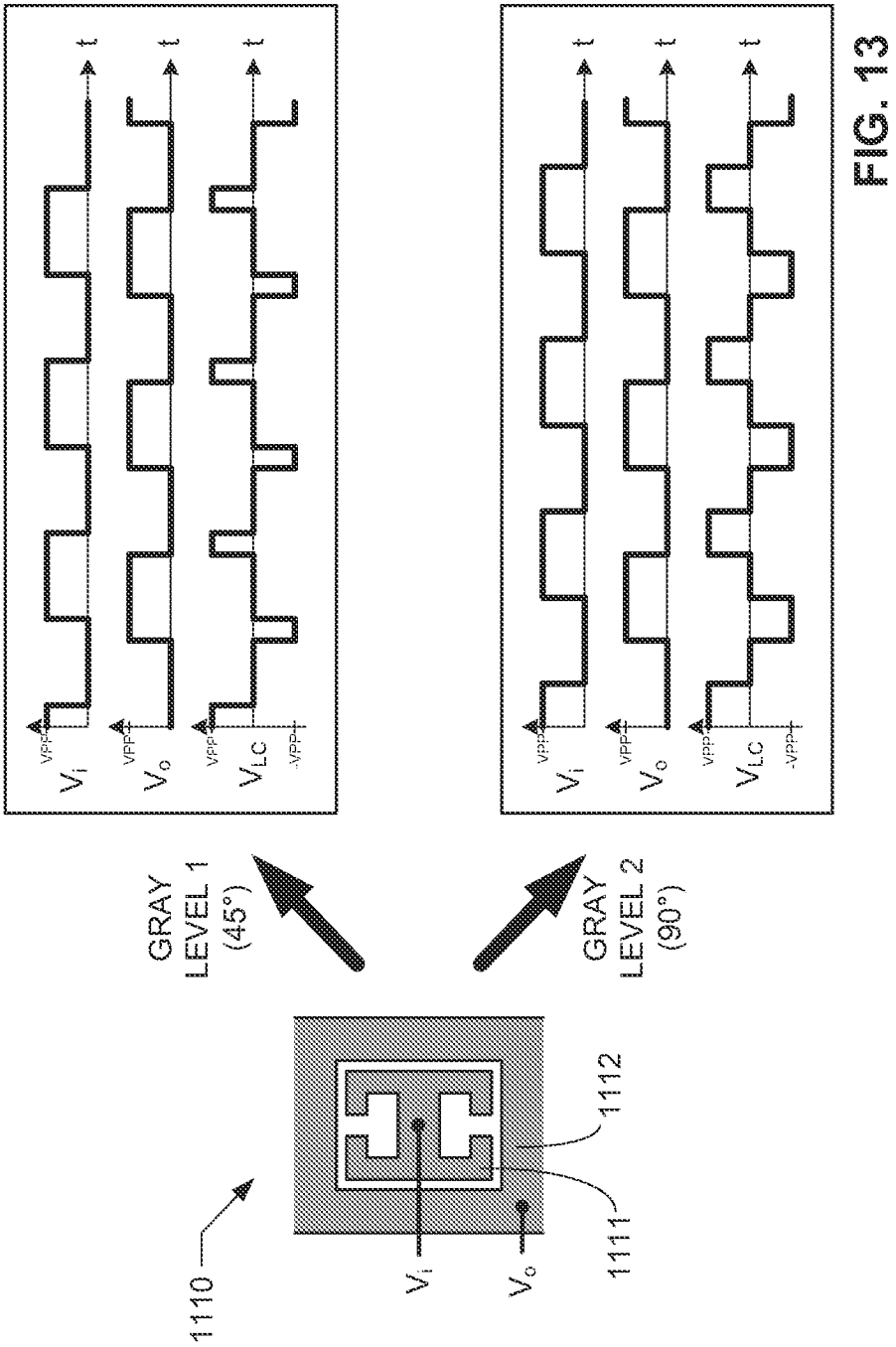

GRAY LEVEL 1 (45°)
GRAY LEVEL 2 (90°)
1110
1111
1112
V_i
V_o
V_{LC}
t
VPP
-VPP

FIG. 13

FIG. 14

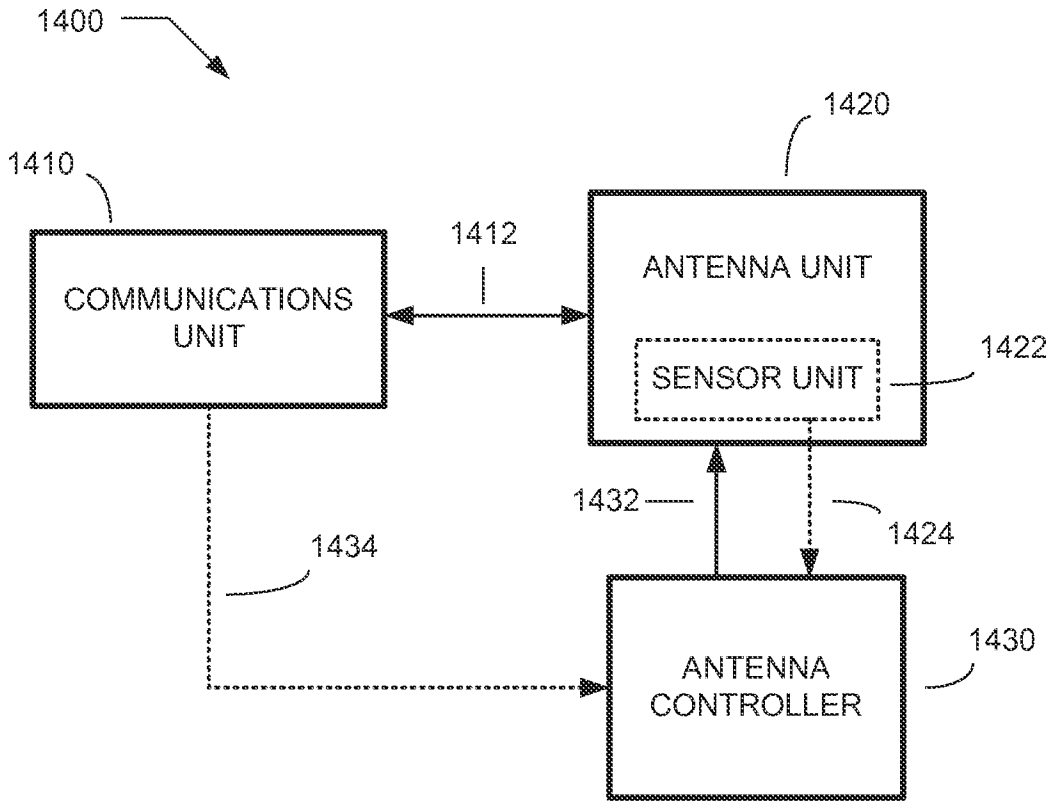

1400
1410
1420
1412
COMMUNICATIONS UNIT
ANTENNA UNIT
SENSOR UNIT
1422
1432
1424
1434
ANTENNA CONTROLLER
1430

FIG. 15

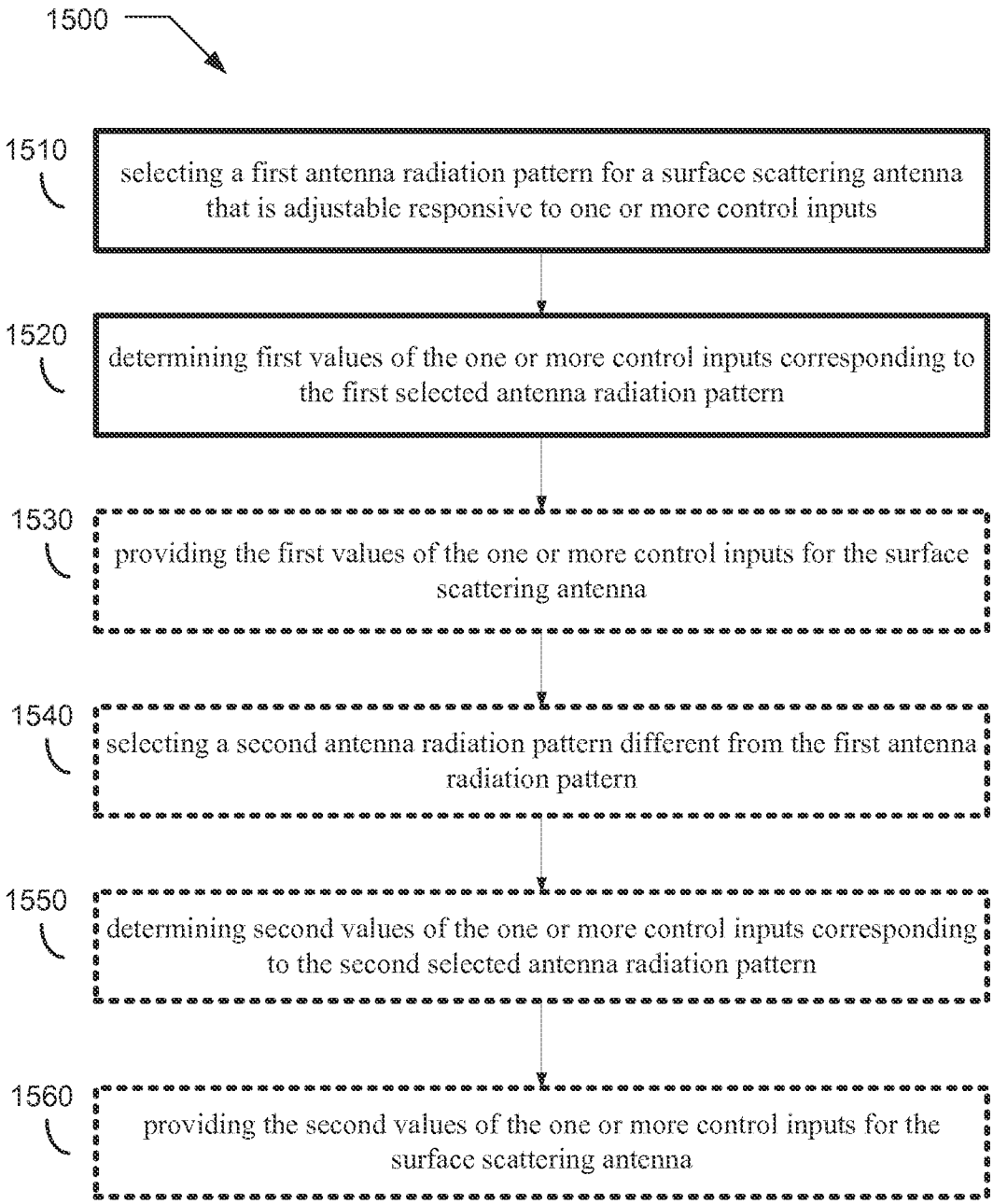
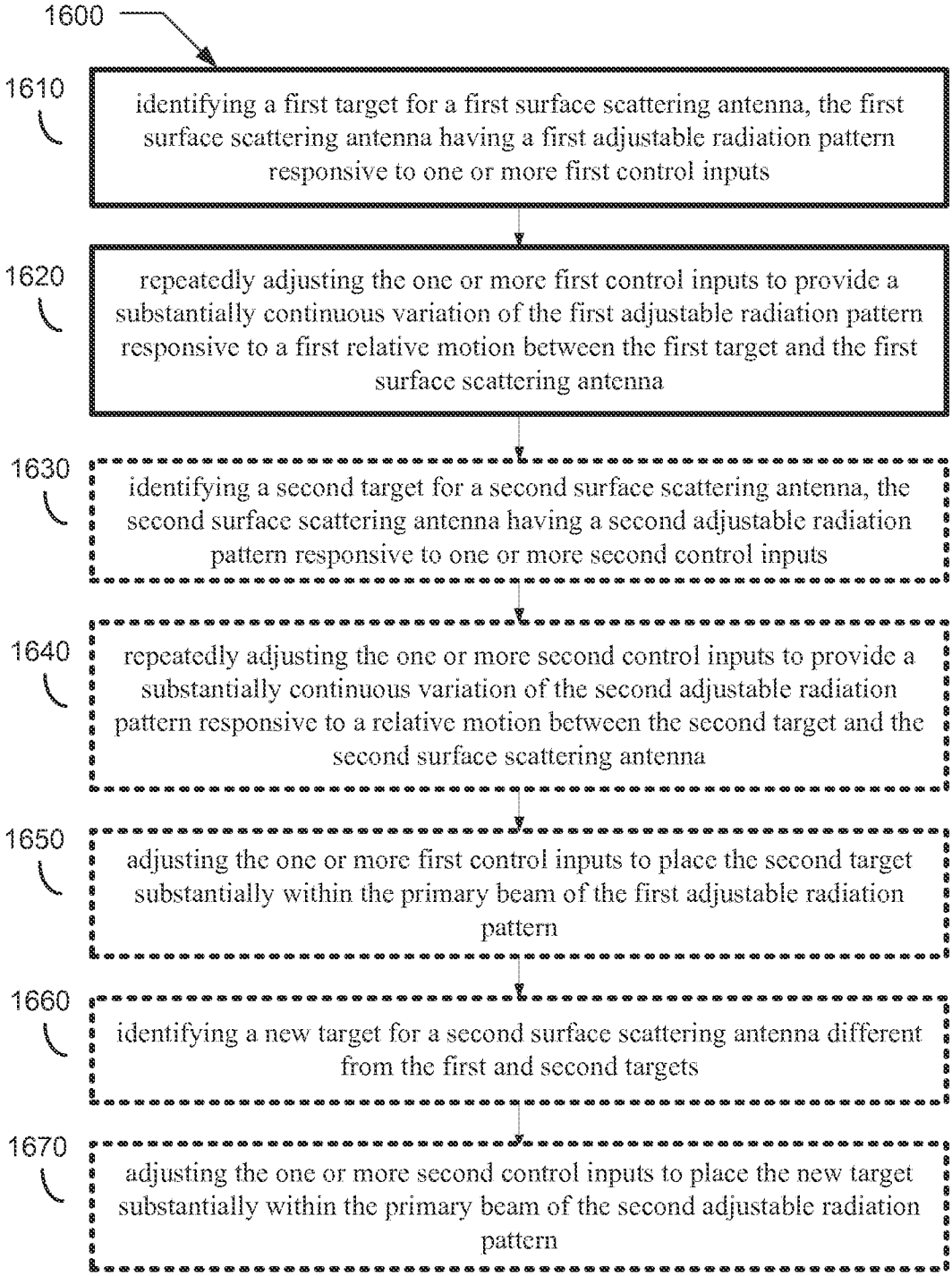

1500
1510
selecting a first antenna radiation pattern for a surface scattering antenna that is adjustable responsive to one or more control inputs
1520
determining first values of the one or more control inputs corresponding to the first selected antenna radiation pattern
1530
providing the first values of the one or more control inputs for the surface scattering antenna
1540
selecting a second antenna radiation pattern different from the first antenna radiation pattern
1550
determining second values of the one or more control inputs corresponding to the second selected antenna radiation pattern
1560
providing the second values of the one or more control inputs for the surface scattering antenna

FIG. 16


1600
1610
identifying a first target for a first surface scattering antenna, the first surface scattering antenna having a first adjustable radiation pattern responsive to one or more first control inputs
1620
repeatedly adjusting the one or more first control inputs to provide a substantially continuous variation of the first adjustable radiation pattern responsive to a first relative motion between the first target and the first surface scattering antenna
1630
identifying a second target for a second surface scattering antenna, the second surface scattering antenna having a second adjustable radiation pattern responsive to one or more second control inputs
1640
repeatedly adjusting the one or more second control inputs to provide a substantially continuous variation of the second adjustable radiation pattern responsive to a relative motion between the second target and the second surface scattering antenna
1650
adjusting the one or more first control inputs to place the second target substantially within the primary beam of the first adjustable radiation pattern
1660
identifying a new target for a second surface scattering antenna different from the first and second targets
1670
adjusting the one or more second control inputs to place the new target substantially within the primary beam of the second adjustable radiation pattern

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/017454

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01Q 13/00 (2014.01)
USPC - 343/772
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)
IPC(8) - H01Q 1/00, 13/00, 13/20, H01P 3/0 (2014.01)
USPC - 333/239, 343/700R, 772

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - H01Q 13/06, 13/20, 13/28 (2014.02)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012/0194399 A1 (BILY et al) 02 August 2012 (02.08.2012) entire document	1-25
Y	OVI et al. "Symmetrical Slot Loading in Elliptical Microstrip Patch Antennas Partially Filled with Mue Negative Metamaterials," PIERS Proceedings, Moscow, Russia, August 19-23, 2012, pp 542-545, [retrieved on 2014-08-02], Retrieved from the internet: <URL: https://piers.org/piersproceedings/download.php?file=cGllcnMyMDEyTW9zY293fDJBOV8wNTQyLnBkZnwxMjAzMjAyMDE0MjM=> entire document	1-25
Y	US 5,512,906 A (SPECIALE) 30 April 1996 (30.04.1996) entire document	3-11
Y	US 6,211,823 B1 (HERRING et al) 03 April 2001 (03.04.2001) entire document	11, 15-16, and 22-23
Y	US 3,714,608 A (BARNES et al) 30 January 1973 (30.01.1973) entire document	17-18 and 24-25

☐ 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	Date of mailing of the international search report
11 August 2014	28 AUG 2014
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/017454

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.:
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:

3. ☐ Claims Nos.:
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:
see last page

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 additional fees, this Authority did not invite payment of 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.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/017454

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-11, drawn to an antenna comprising a wave propagating structure and subwavelength patch elements.
Group II, claims 12-25, drawn to a method of propagating first and second guided waves to radiate elliptically polarized waves producing radiation fields.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: plurality of subwavelength patch elements distributed along the wavepropagating structure with inter-element spacings substantially less than a freespace wavelength corresponding to an operating frequency of the antenna, where the plurality of subwavelength patch elements have a plurality of adjustable individual electromagnetic responses to a guided wave mode as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: propagating a first guided wave to deliver a first plurality of relative phases to a respective plurality of locations; coupling to the first guided wave at a first set of locations selected from the respective plurality of locations to radiate a first plurality of elliptically polarized waves from the first set of locations, the first plurality of elliptically polarized waves producing a first radiation field; propagating a second guided wave to deliver a second plurality of relative phases to the respective plurality of locations, where the second plurality of relative phases is substantially equal to the first plurality of relative phases; and coupling to the second guided wave at a second set of locations selected from plurality of locations to radiate a second plurality of elliptically-polarized waves from the second set of locations, the second plurality of elliptically-polarized waves producing a second radiation field different from the first radiation field as claimed therein is not present in the invention of Groups I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of wave propagation comprising guided waves and producing a radiation field, this technical feature is not a special technical feature as it does not make a contribution over the prior art. Specifically, US 2012/0194399 A1 (BILY et al) 02 August 2012 (02.08.2012) teaches an antenna (abstract) comprising a wave propagating structure (para 18, element 104), guided waves and producing a radiation field (para 18, 22).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.