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Behdad et al.

(10) **Patent No.: US 9,640,867 B2**
(45) **Date of Patent: May 2, 2017**

(54) **TUNABLE SPATIAL PHASE SHIFTER**

(71) Applicant: **Wisconsin Alumni Research Foundation**, Madison, WI (US)

(72) Inventors: **Nader Behdad**, Madison, WI (US); **John Booske**, McFarland, WI (US)

(73) Assignee: **Wisconsin Alumni Research Foundation**, Madison, WI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 127 days.

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(22) Filed: **Mar. 30, 2015**

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US 2016/0294054 A1 Oct. 6, 2016

(51) **Int. Cl.**

H01Q 3/36	(2006.01)
H01Q 3/32	(2006.01)
H01Q 21/06	(2006.01)
H01P 1/18	(2006.01)

(52) **U.S. Cl.**

CPC ***H01Q 3/32*** (2013.01); ***H01Q 3/36*** (2013.01); ***H01Q 21/061*** (2013.01); *H01P 1/18* (2013.01)

(58) **Field of Classification Search**

CPC H01Q 15/04; H01Q 15/0026; H01Q 3/32
USPC 343/746
See application file for complete search history.

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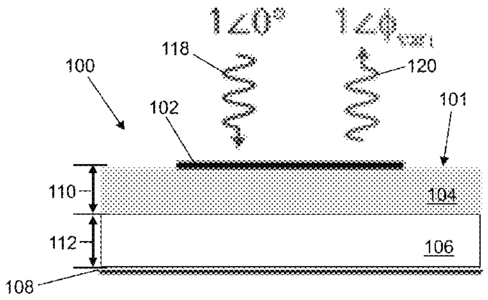
Primary Examiner — Huedung Mancuso
(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

A tunable phase shifter is provided that includes a spatial phase shift element and a conducting sheet. The spatial phase shift element includes a dielectric substrate and a conductive antenna element mounted on the dielectric substrate. The conducting sheet is mounted a distance from the spatial phase shift element and configured to reflect an electromagnetic wave through the spatial phase shift element. The conductive antenna element is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave. The distance between the conducting sheet and the spatial phase shift element can be changed to adjust a phase shift of the reflected electromagnetic wave.

20 Claims, 21 Drawing Sheets



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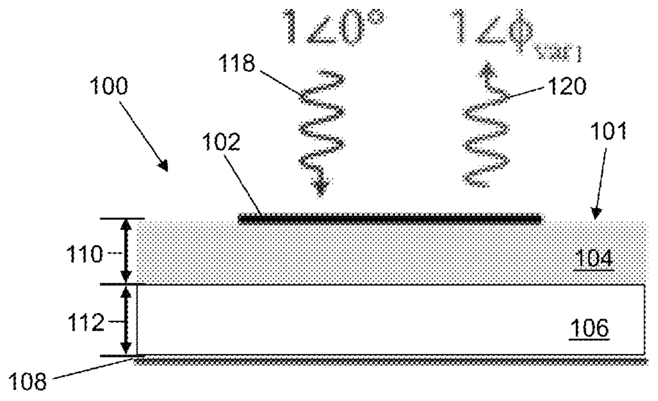
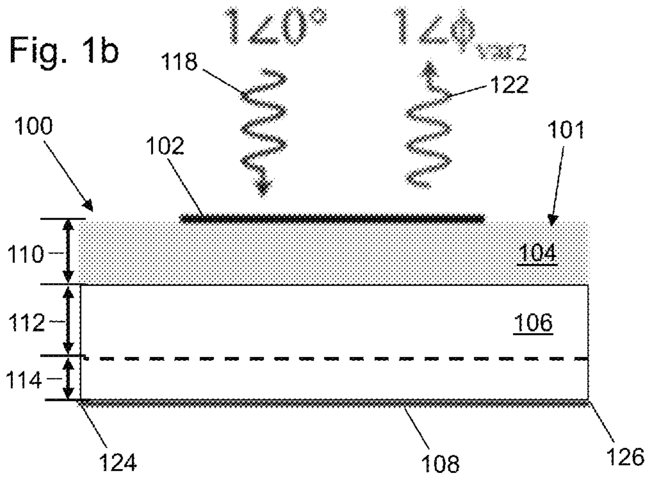


Fig. 1a

Fig. 1b



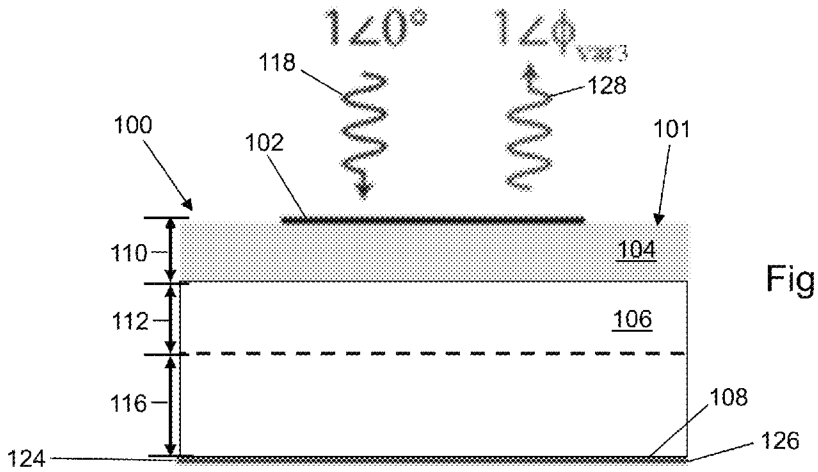


Fig. 1c

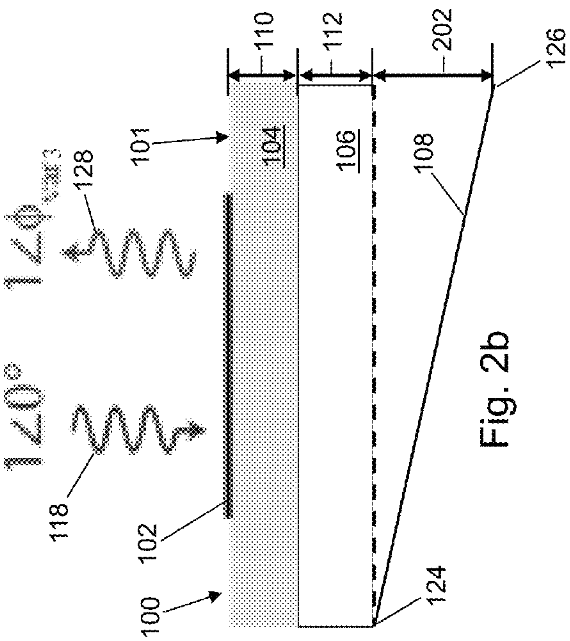
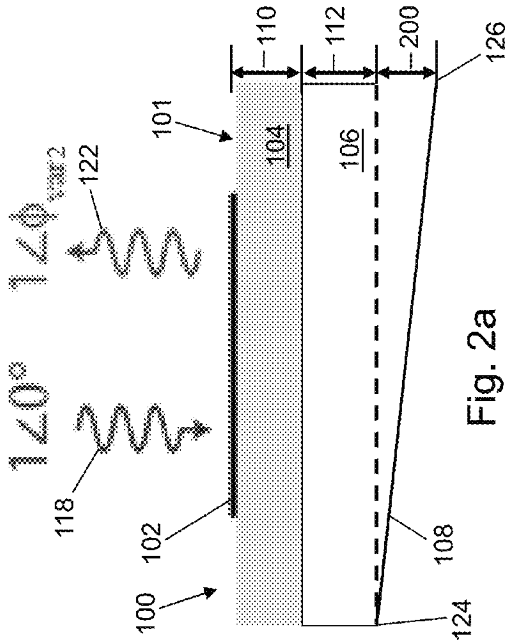


Fig. 2b



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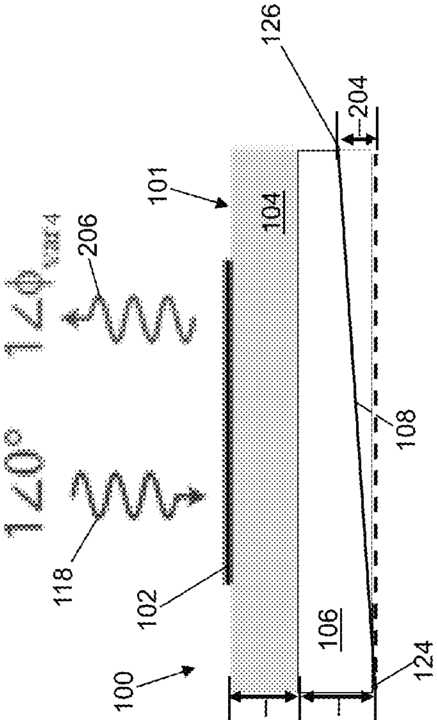


Fig. 2c

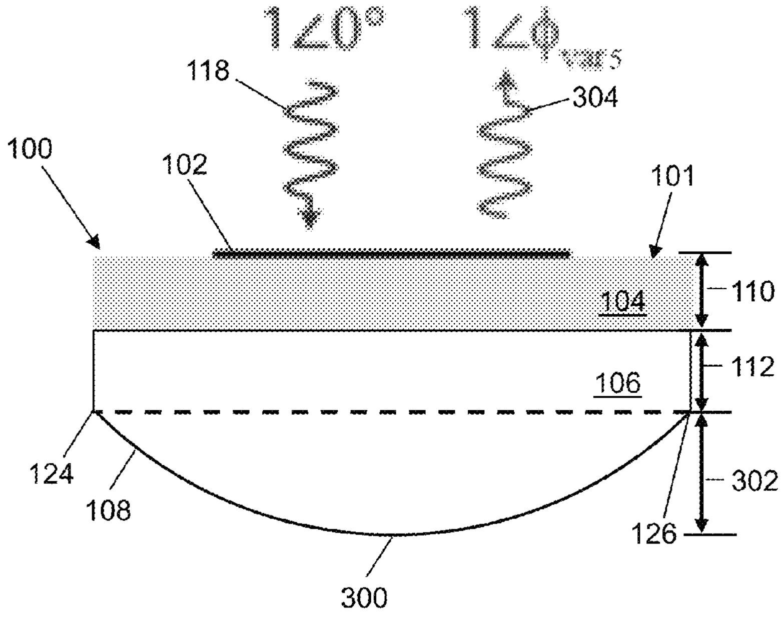
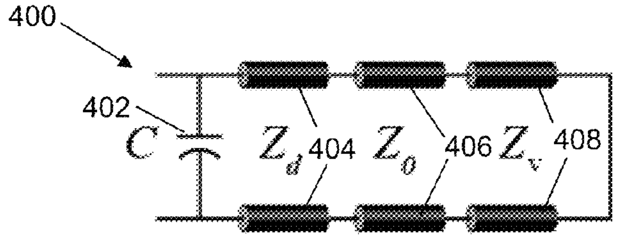


Fig. 3



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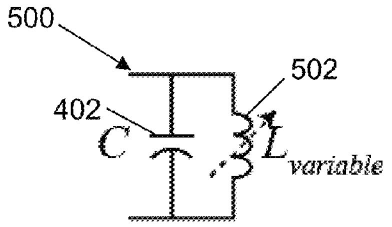

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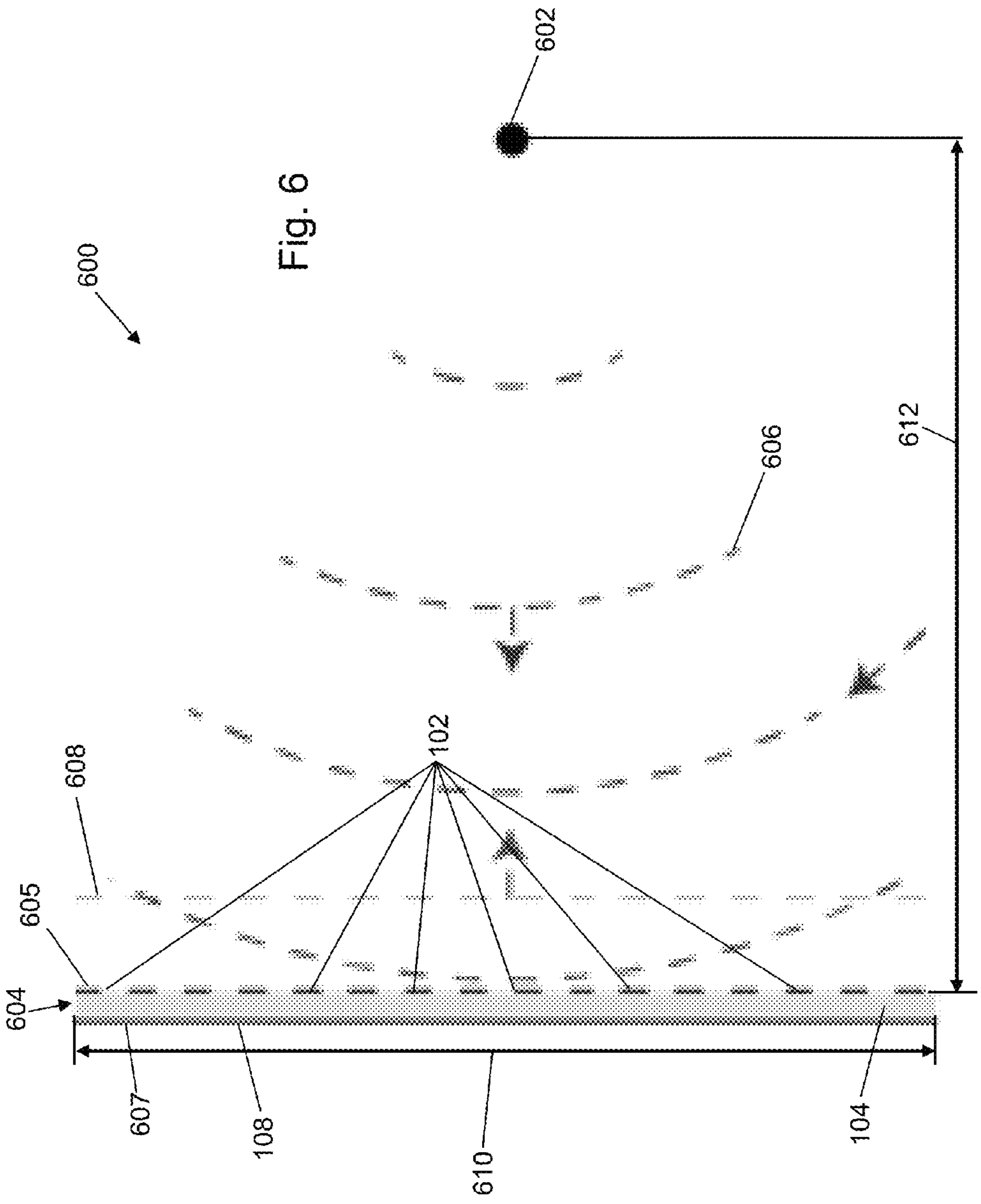

Fig. 6

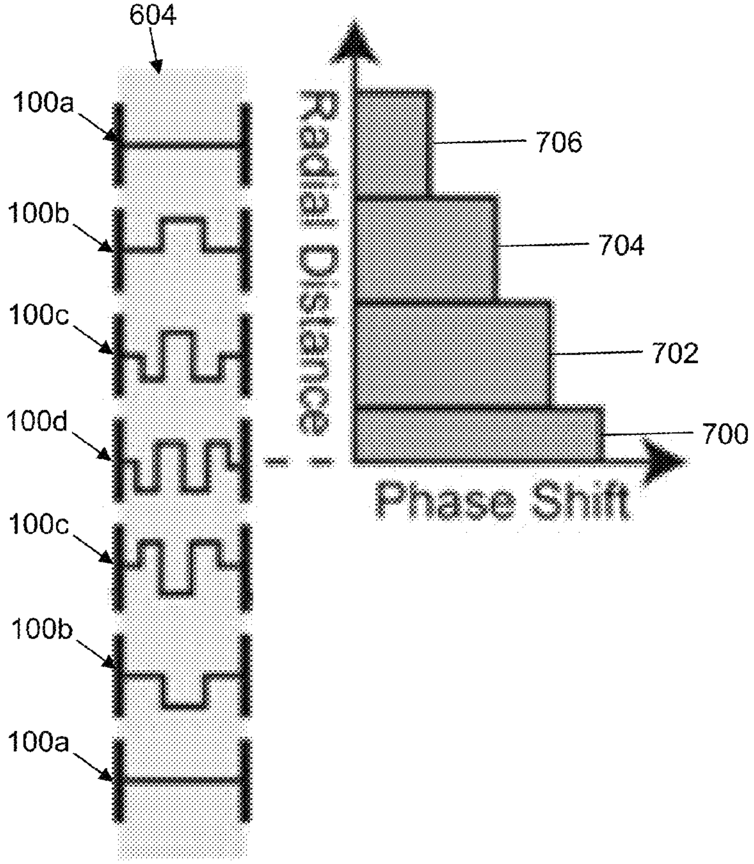
604
100a
100b
100c
100d
100c
100b
100a
Radial Distance
Phase Shift
706
704
702
700

Fig. 7

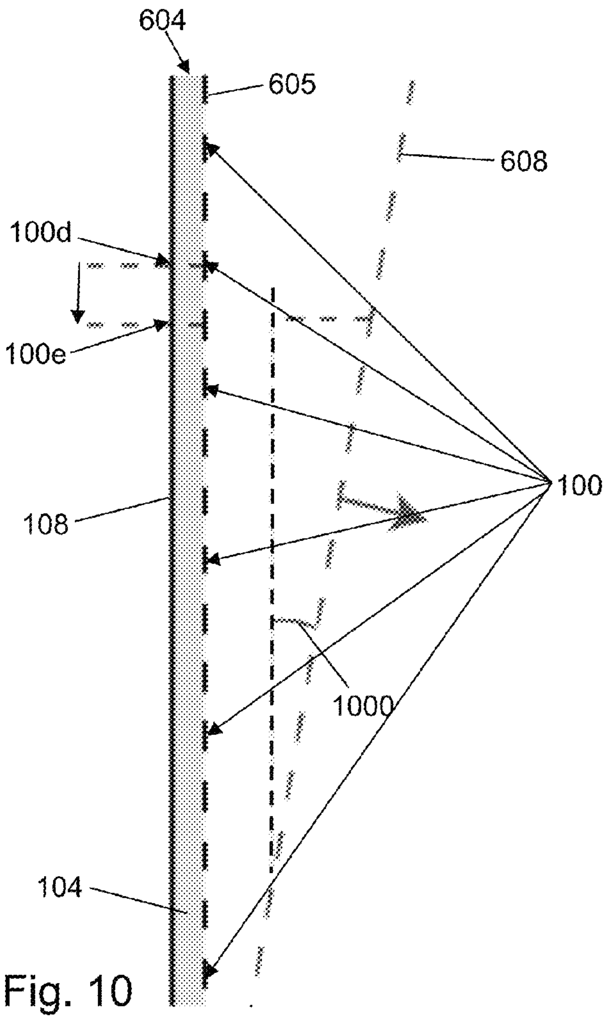
604
605
608
100d
100e
108
100
1000
104

Fig. 10

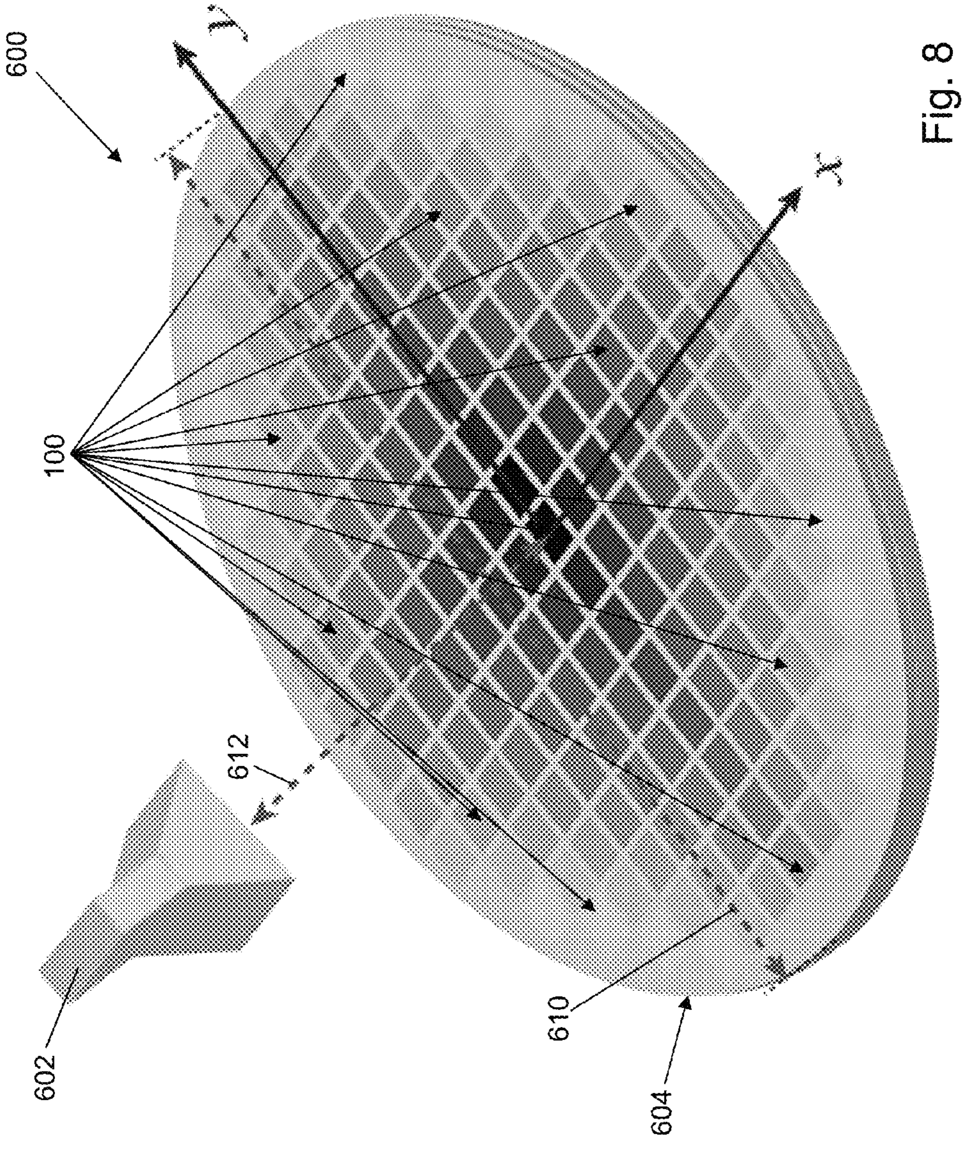

Fig. 8

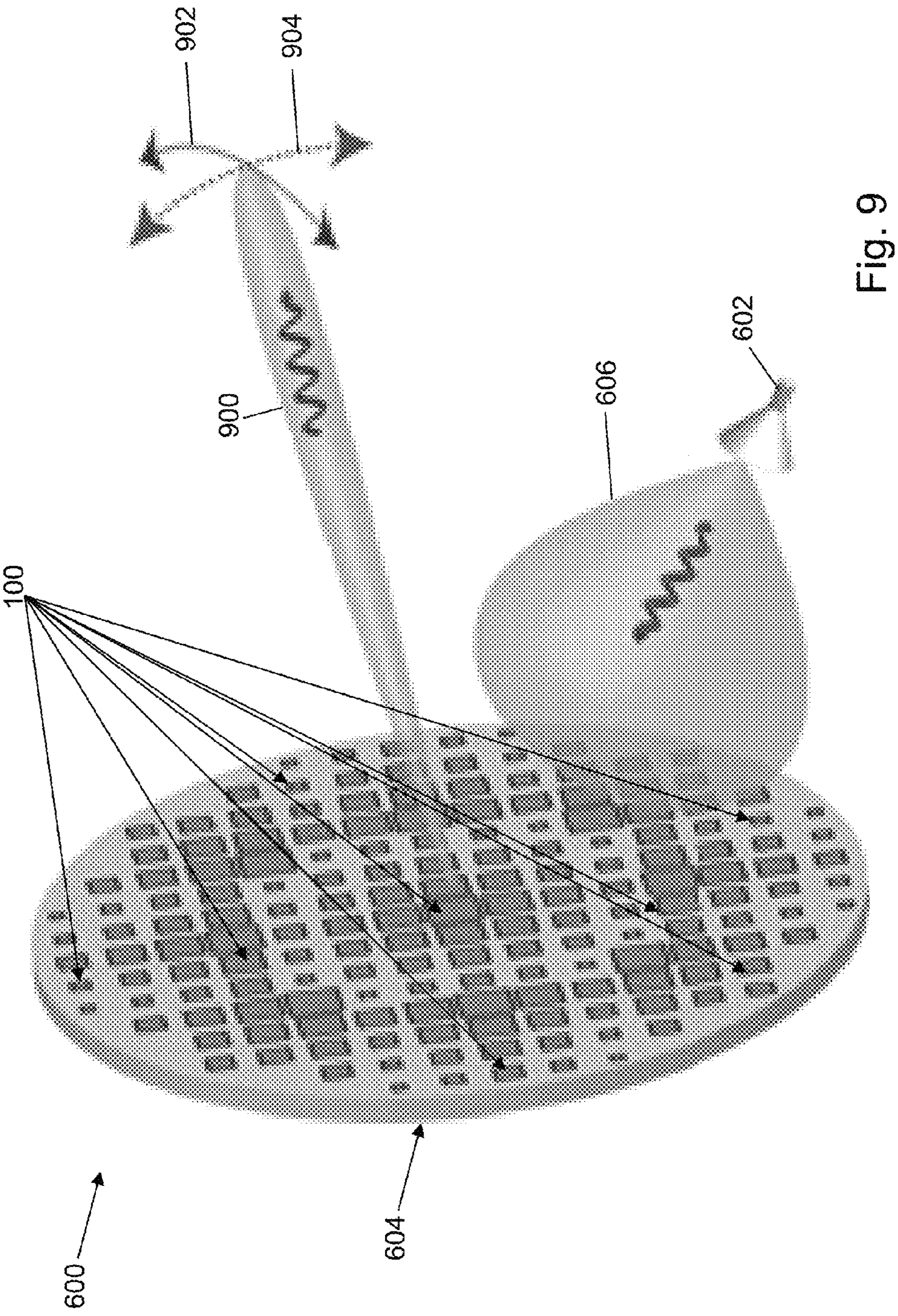

Fig. 9

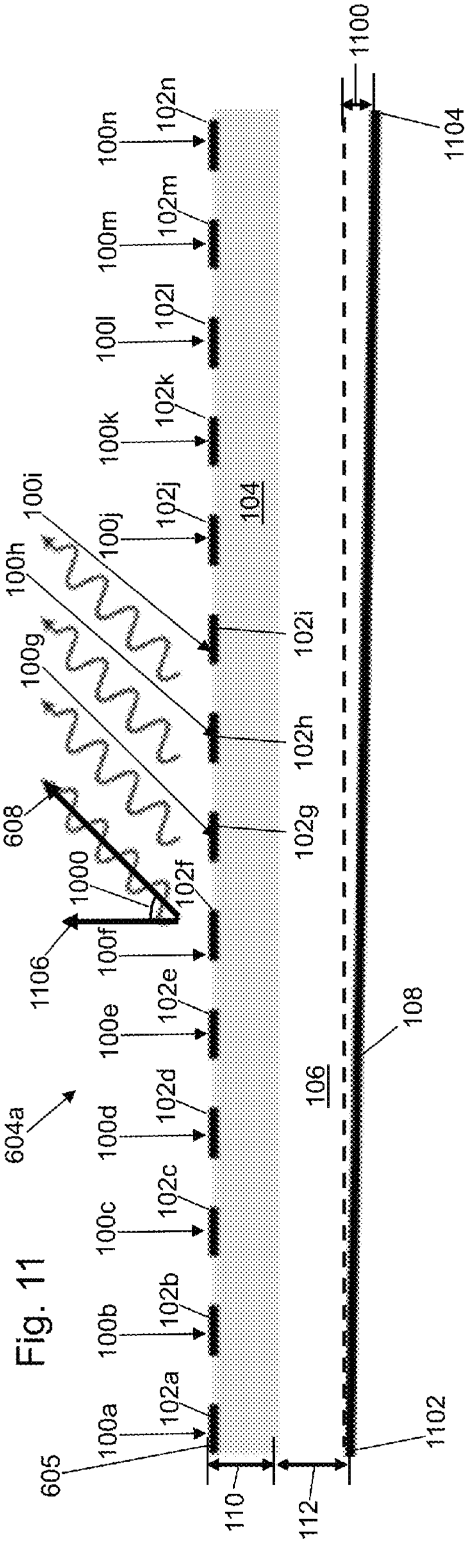
Fig. 11

604a
605
100a
100b
100c
100d
100e
100f
100g
100h
100i
100j
100k
100l
100m
100n
102a
102b
102c
102d
102e
102f
102g
102h
102i
102j
102k
102l
102m
102n
104
106
108
110
112
608
1000
1100
1102
1104
1106

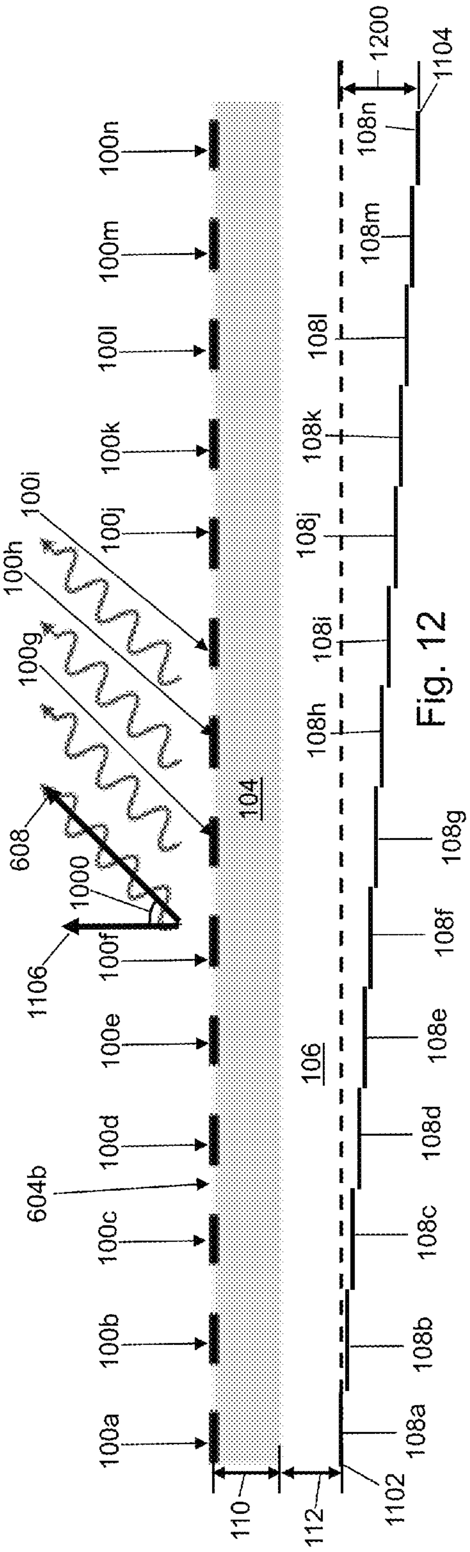
Fig. 12

604b
100a
100b
100c
100d
100e
100f
100g
100h
100i
100j
100k
100l
100m
100n
104
106
108a
108b
108c
108d
108e
108f
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1000
1102
1104
1106
1200

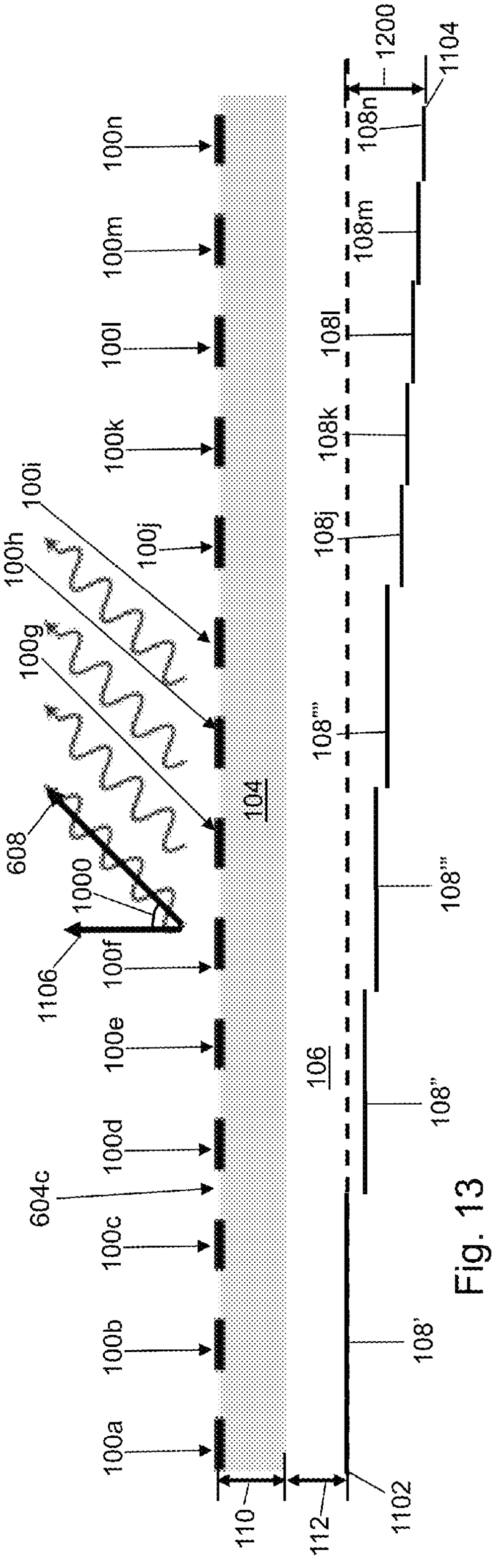

100a
100b
100c
604c
100d
100e
100f
1106
1000
608
100g
100h
100i
100j
100k
100l
100m
100n
104
106
108'
108"
108"
108'"
108j
108k
108l
108m
108n
1200
1104
110
112
1102

Fig. 13

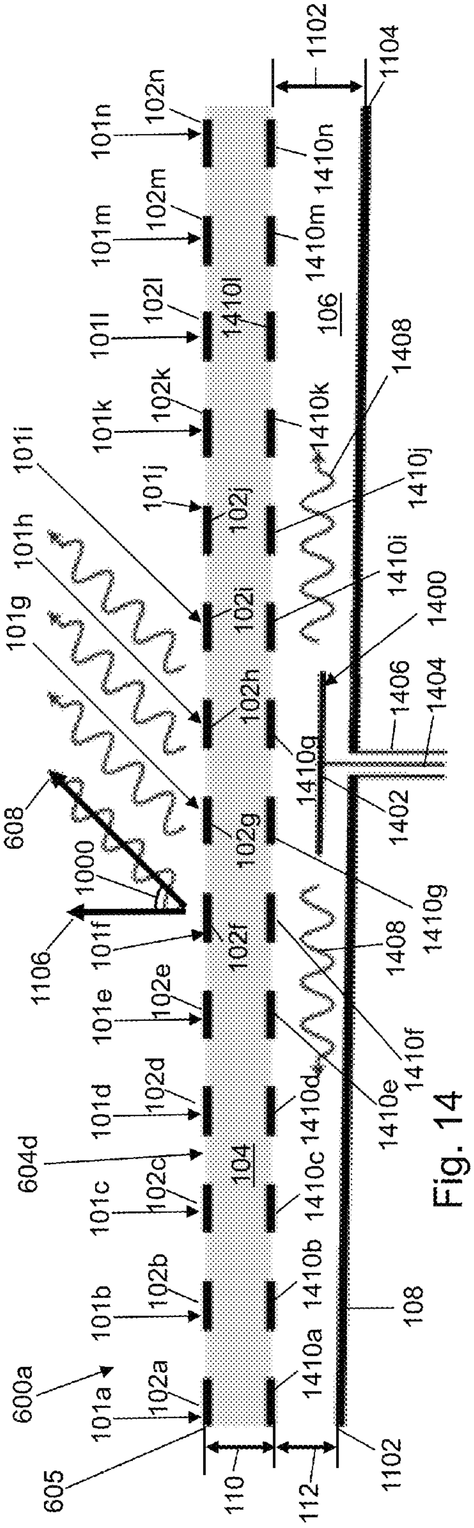

600a
605
101a
102a
101b
102b
101c
102c
604d
101d
102d
101e
102e
101f
102f
1106
1000
608
101g
102g
101h
102h
101i
102i
101j
102j
101k
102k
101l
102l
101m
102m
101n
102n
104
106
1410a
1410b
1410c
1410d
1410e
1410f
1410g
1410g
1410i
1410j
1410k
1410l
1410m
1410n
1408
1408
1400
1402
1404
1406
1102
1104
108
110
112
1102

Fig. 14

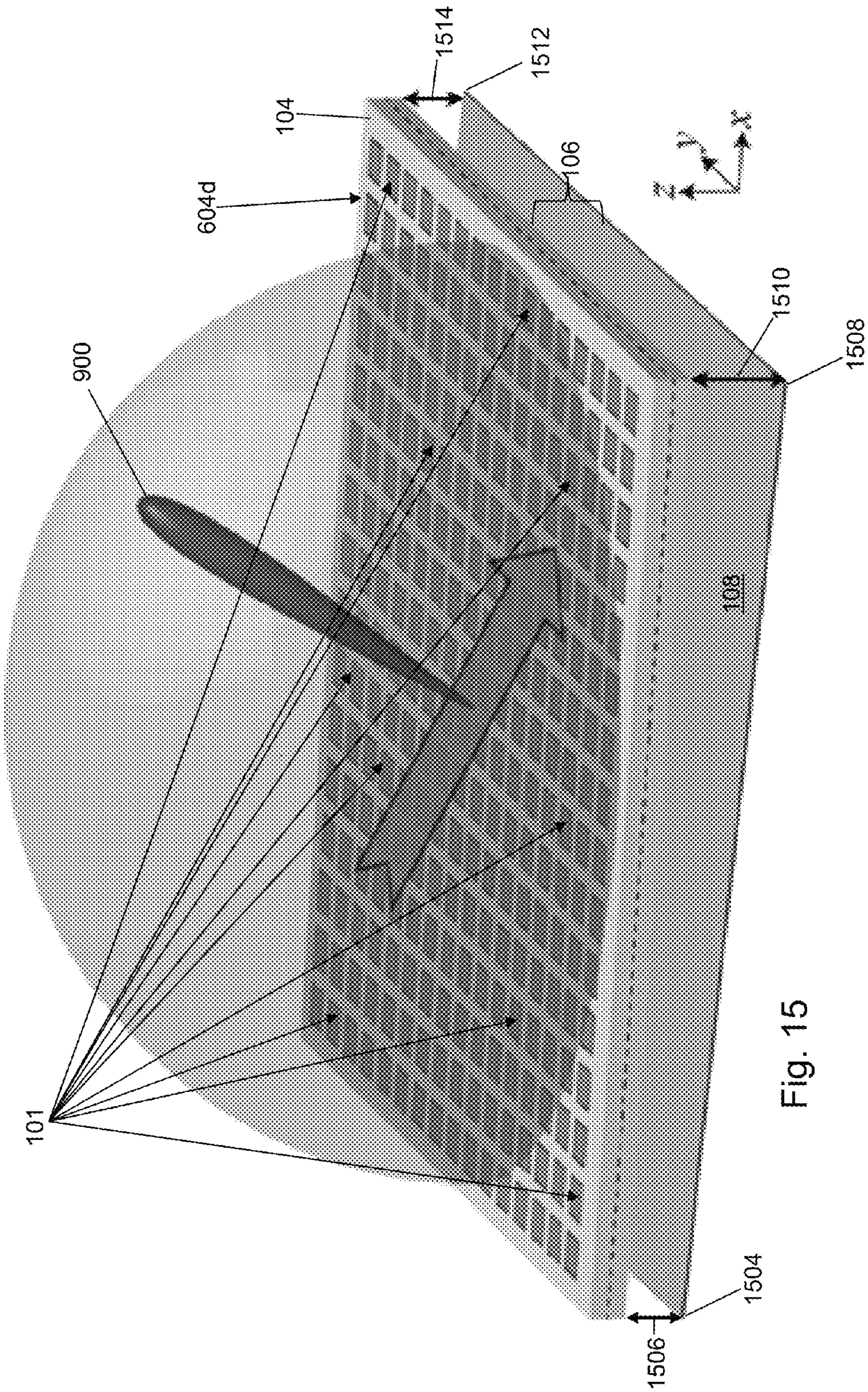


Fig. 15

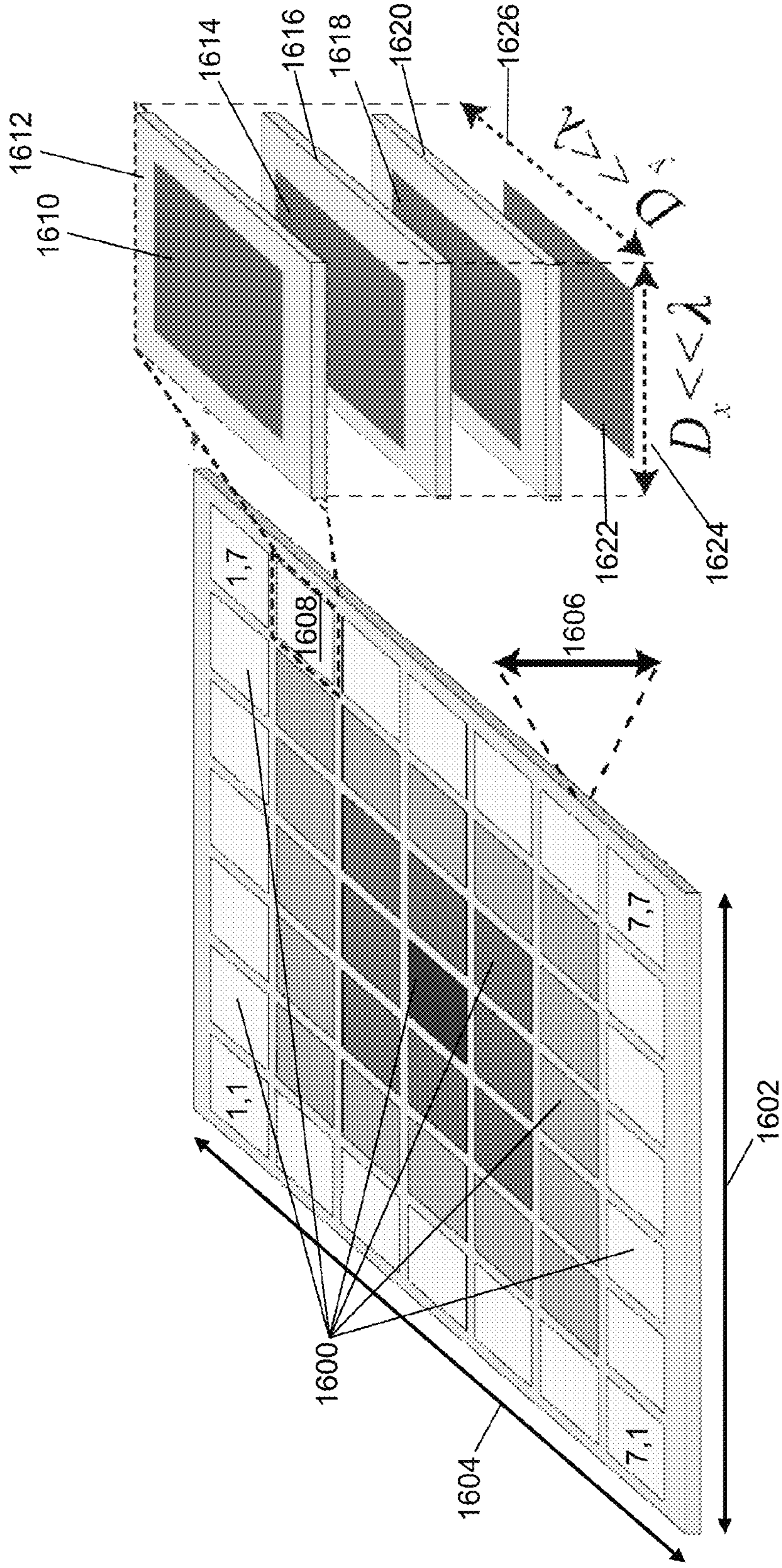

1612
1610
1614
1616
1618
1620
1626
$D_y << \lambda$
$D_x << \lambda$
1622
1624
1,7
1608
1606
1,1
7,7
7,1
1600
1604
1602

Fig. 16

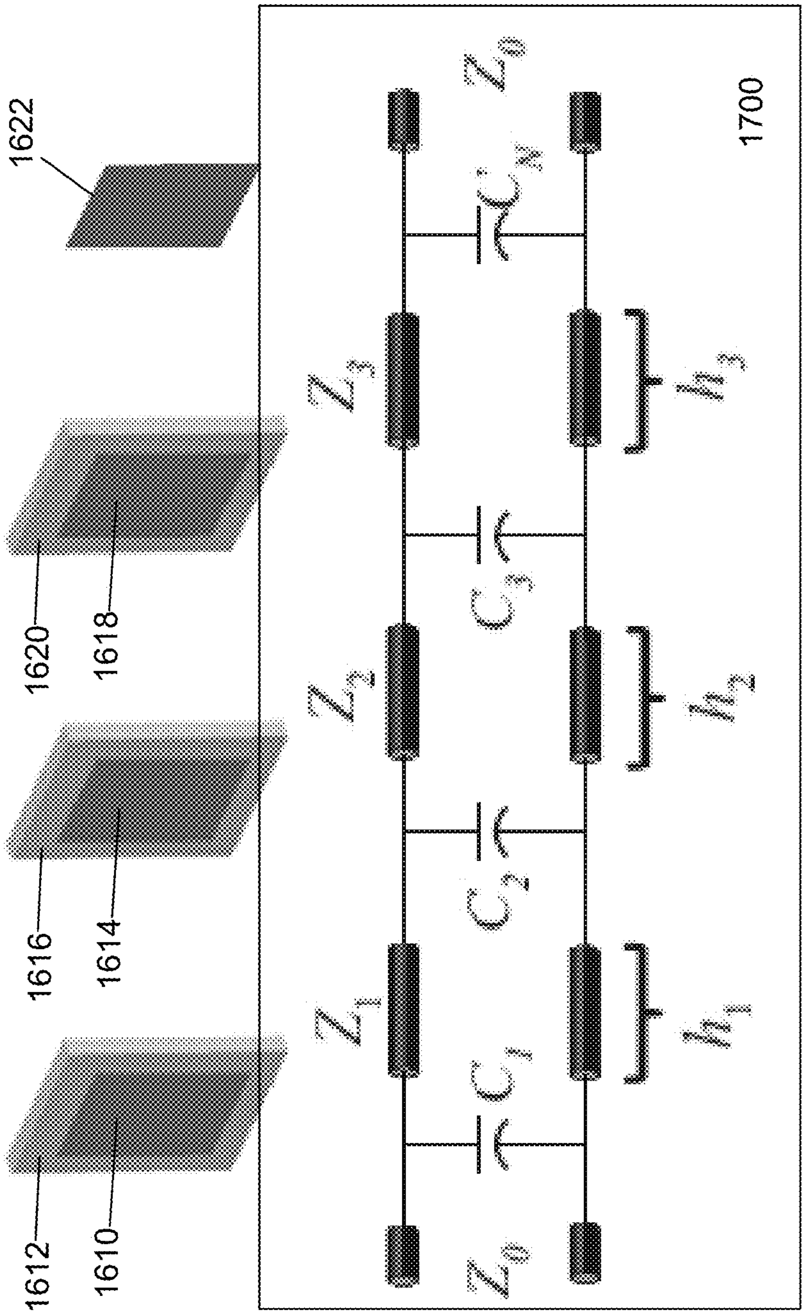

1612
1610
1616
1614
1620
1618
1622
Z_0
C_1
Z_1
h_1
C_2
Z_2
h_2
C_3
Z_3
h_3
C_N
Z_0
1700

Fig. 17

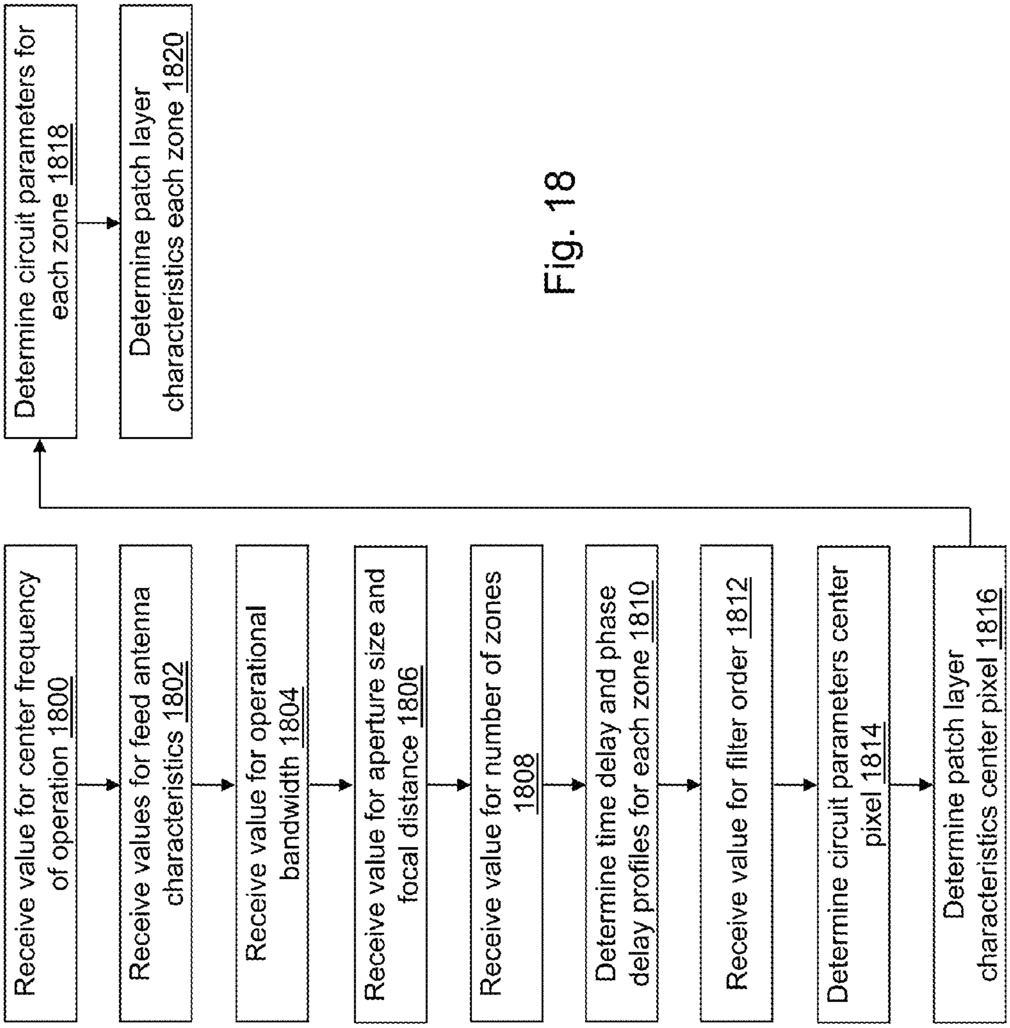

Receive value for center frequency of operation 1800
Receive values for feed antenna characteristics 1802
Receive value for operational bandwidth 1804
Receive value for aperture size and focal distance 1806
Receive value for number of zones 1808
Determine time delay and phase delay profiles for each zone 1810
Receive value for filter order 1812
Determine circuit parameters center pixel 1814
Determine patch layer characteristics center pixel 1816
Determine circuit parameters for each zone 1818
Determine patch layer characteristics each zone 1820

Fig. 18

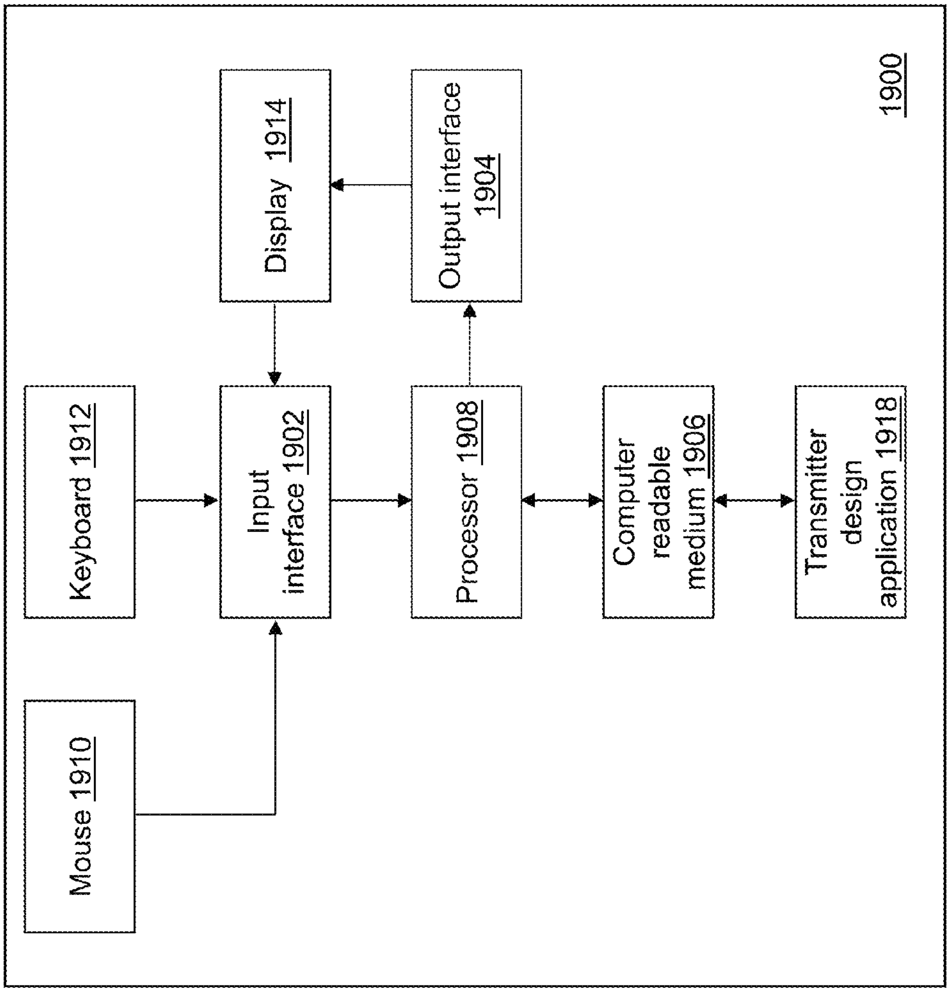

Mouse 1910
Keyboard 1912
Input interface 1902
Display 1914
Output interface 1904
Processor 1908
Computer readable medium 1906
Transmitter design application 1918
1900

Fig. 19

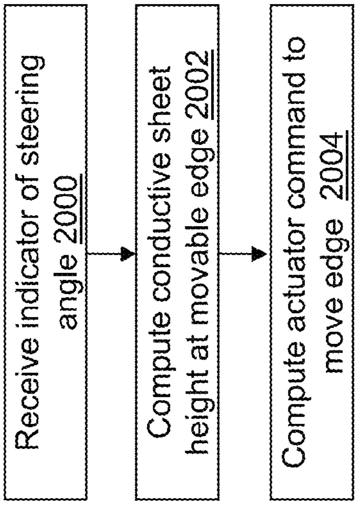

Receive indicator of steering angle 2000
Compute conductive sheet height at movable edge 2002
Compute actuator command to move edge 2004

Fig. 20

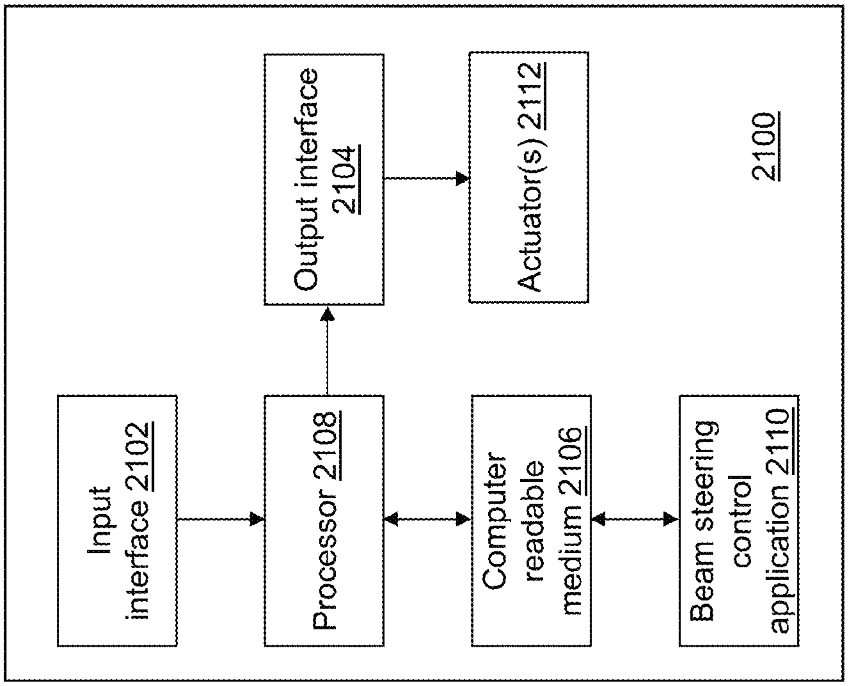

Input interface 2102
Processor 2108
Computer readable medium 2106
Beam steering control application 2110
Output interface 2104
Actuator(s) 2112
2100

Fig. 21

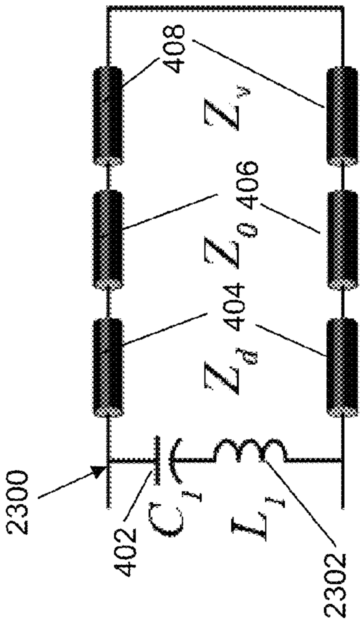


Fig. 23

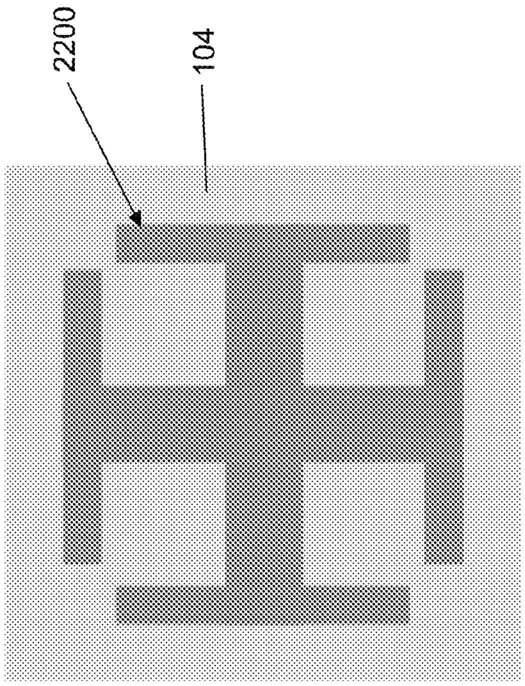


Fig. 22

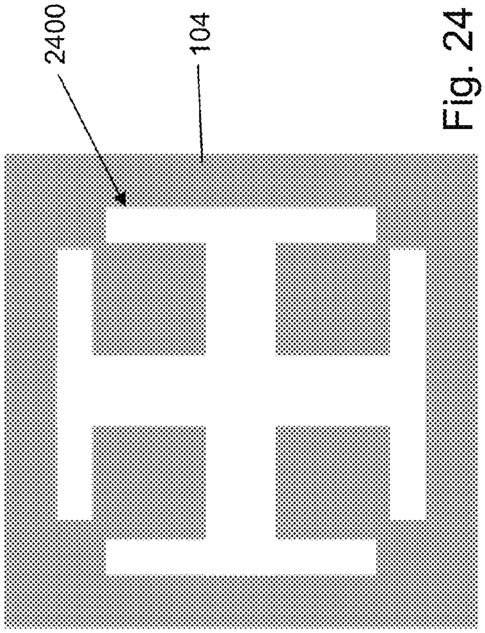


Fig. 24

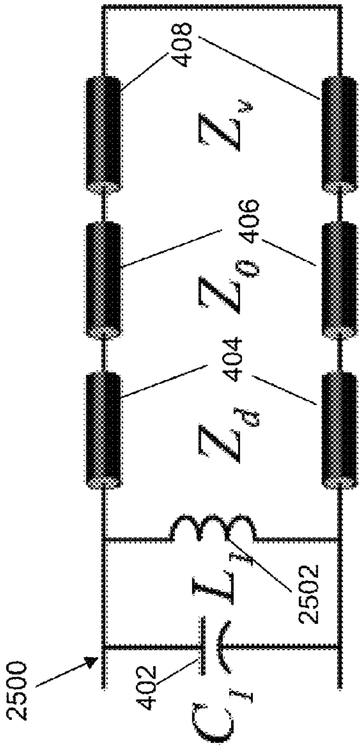


Fig. 25

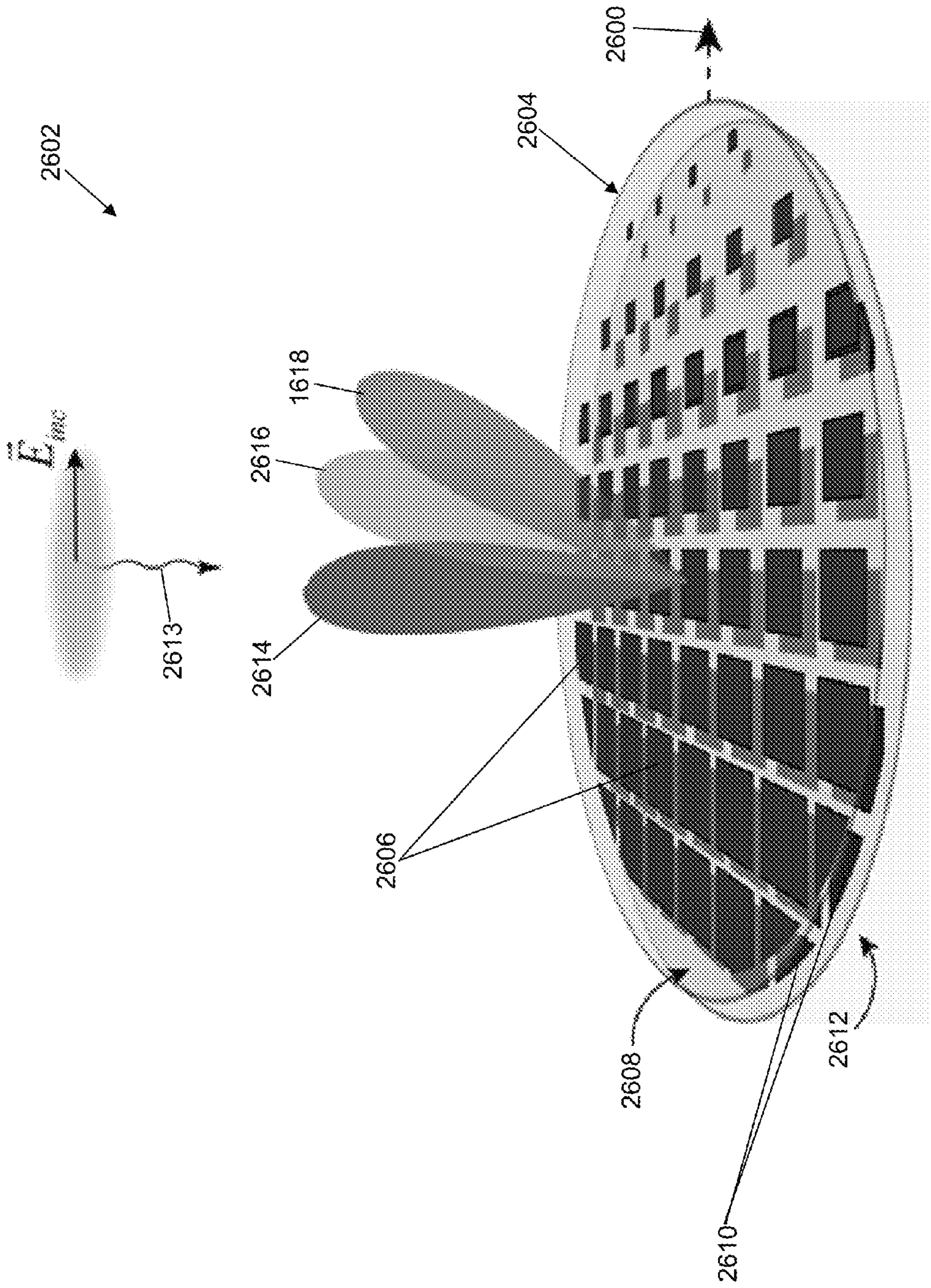

2602
$\vec{E}_{inc}$
2613
2614
2616
1618
2600
2604
2606
2608
2610
2612

Fig. 26

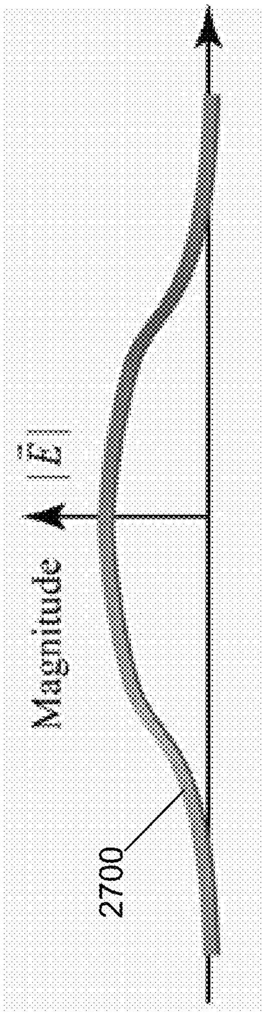


Fig. 27a

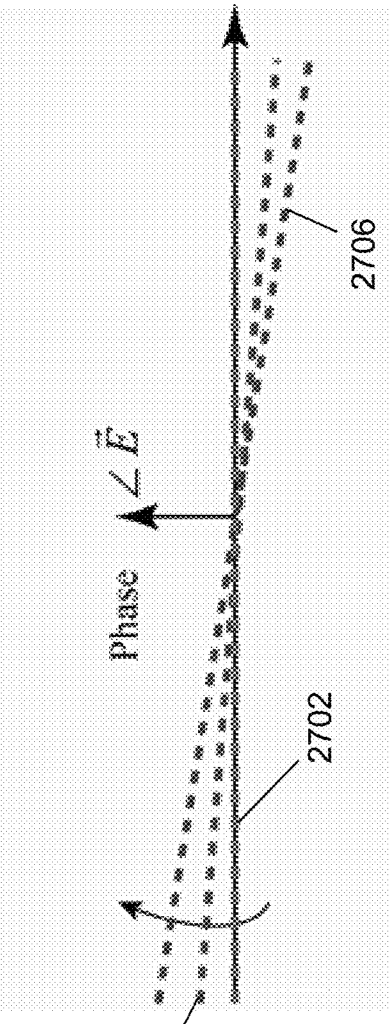
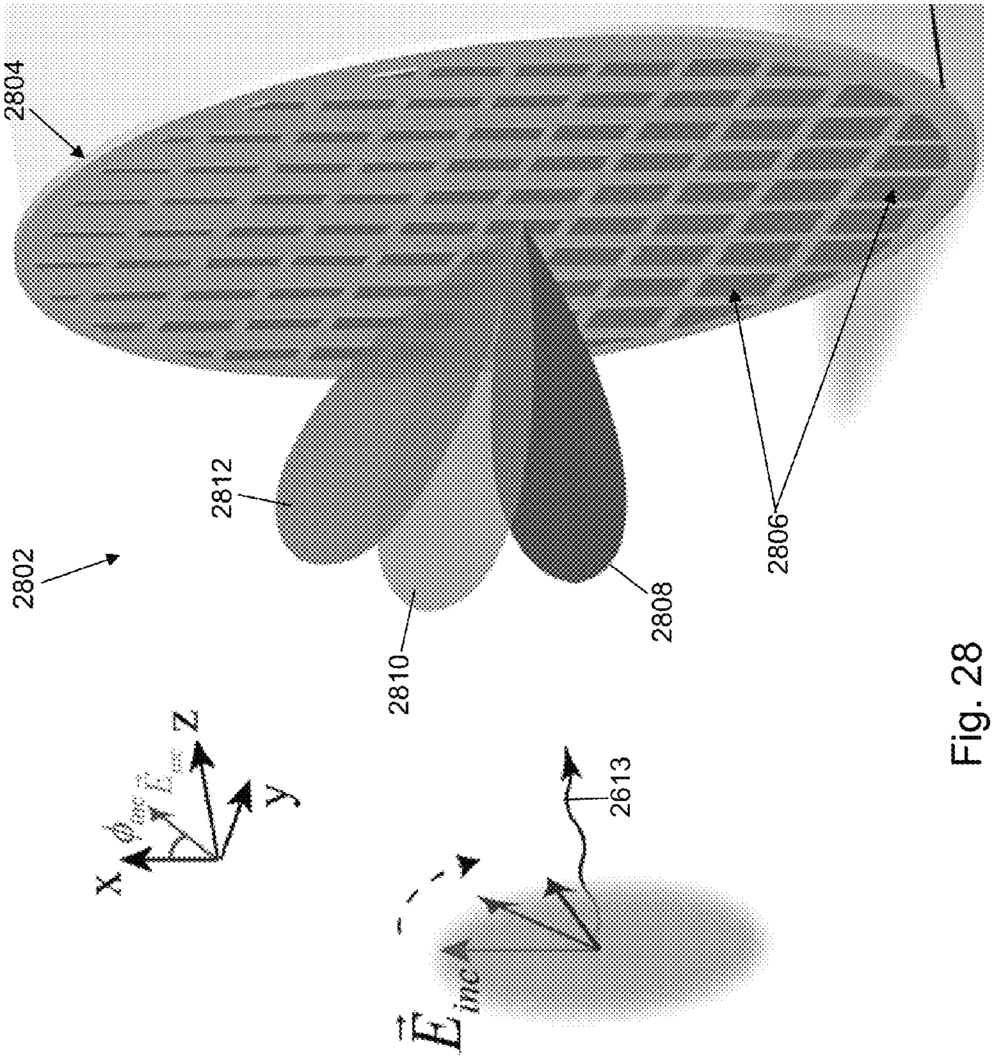


Fig. 27b


2804
2802
2812
2810
2808
2806
x
y
z
ϕ_{inc}
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2613
$\vec{E}_{inc}$

Fig. 28

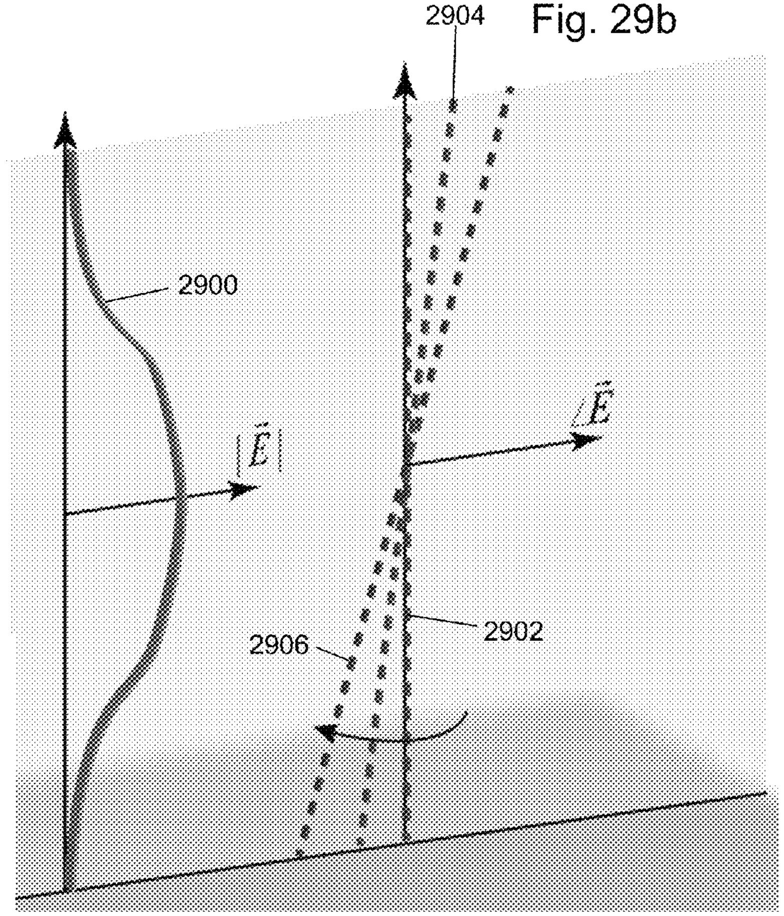

Fig. 29b

Fig. 29a

TUNABLE SPATIAL PHASE SHIFTER

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under 1101146 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

A phased array antenna is an array of antennas in which a relative phase of signals feeding the antennas is varied such that an effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions to provide electronic steering of a beam. To convert a reflector array into a beam steerable antenna, a phase shift distribution provided by spatial phase shifting pixels must be dynamically changed depending on the direction of the desired output beam in the far field. Conventionally, this is achieved by changing a capacitance provided by capacitive patches by loading them with varactors or switches.

SUMMARY

In an illustrative embodiment, a tunable phase shifter is provided. The tunable phase shifter includes, but is not limited to, a spatial phase shift element and a conducting sheet. The spatial phase shift element includes, but is not limited to, a dielectric substrate and a conductive antenna element mounted on the dielectric substrate. The conducting sheet is mounted a distance from the spatial phase shift element and is configured to reflect an electromagnetic wave through the spatial phase shift element. The conductive antenna element is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave. The distance between the conducting sheet and the spatial phase shift element can be changed to adjust a phase shift of the reflected electromagnetic wave.

In another illustrative embodiment, a phased array antenna is provided. The phased array antenna includes, but is not limited to, a feed antenna and a plurality of spatial phase shift elements distributed linearly in a direction. The feed antenna is configured to radiate an electromagnetic wave. Each spatial phase shift element of the plurality of spatial phase shift elements includes, but is not limited to, a dielectric substrate and a conductive antenna element mounted on the dielectric substrate. The conducting sheet is mounted a distance from the plurality of spatial phase shift elements and is configured to reflect an electromagnetic wave through the plurality of spatial phase shift elements. The conductive antenna element of each of the plurality of spatial phase shift elements is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave. The distance between the conducting sheet and the plurality of spatial phase shift elements can be changed to adjust a phase shift of the reflected electromagnetic wave.

In yet another illustrative embodiment, a phased array antenna is provided. The phased array antenna includes, but is not limited to, a feed antenna and a radiating antenna. The feed antenna is configured to radiate an electromagnetic wave. The radiating antenna includes, but is not limited to, a plurality of spatial phase shift elements distributed linearly in a direction and an actuator. Each spatial phase shift element of the plurality of spatial phase shift elements includes, but is not limited to, a dielectric substrate and a conductive antenna element mounted on the dielectric substrate. The conducting sheet is mounted a distance from the plurality of spatial phase shift elements and is configured to reflect the radiated electromagnetic wave through the plurality of spatial phase shift elements. The conductive antenna element of each of the plurality of spatial phase shift elements is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave. The actuator is mounted to the radiating antenna and is configured to change the distance between the conducting sheet and the plurality of spatial phase shift elements.

Other principal features of the disclosed subject matter will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments of the disclosed subject matter will hereafter be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIGS. **1***a*, **1***b*, and **1***c* depict side views of a tunable phase shifter in accordance with an illustrative embodiment with a conducting sheet moved to different positions.

FIGS. **2***a*, **2***b*, and **2***c* depict side views of a second tunable phase shifter in accordance with an illustrative embodiment with a conducting sheet moved to different positions.

FIG. **3** depicts a side view of a third tunable phase shifter in accordance with an illustrative embodiment with a conducting sheet moved to a deflected position.

FIG. **4** depicts an equivalent circuit model of the tunable phase shifters of FIGS. **1***a*-**1***c*, **2***a*-**2***c*, and **3** in accordance with an illustrative embodiment.

FIG. **5** depicts a simplified equivalent circuit model of the tunable phase shifters of FIGS. **1***a*-**1***c*, **2***a*-**2***c*, and **3** in accordance with an illustrative embodiment.

FIG. **6** depicts a side view of a transmitter in accordance with an illustrative embodiment.

FIG. **7** depicts a side view of a plurality of tunable phase shifters in accordance with an illustrative embodiment.

FIG. **8** depicts a perspective view of the transmitter of FIG. **6** in accordance with an illustrative embodiment.

FIG. **9** depicts a perspective view of the transmitter of FIG. **6** with a feed antenna positioned off center relative to the plurality of tunable phase shifters in accordance with an illustrative embodiment.

FIG. **10** depicts a side view of the plurality of tunable phase shifters of FIG. **6** and a resulting planar, collimated reflected wave in accordance with an illustrative embodiment.

FIG. **11** depicts a plurality of tunable phase shifters in accordance with a first illustrative embodiment.

FIG. **12** depicts a plurality of tunable phase shifters in accordance with a second illustrative embodiment.

FIG. **13** depicts a plurality of tunable phase shifters in accordance with a third illustrative embodiment.

FIG. **14** depicts a plurality of tunable phase shifters in accordance with a fourth illustrative embodiment.

FIG. **15** depicts a plurality of tunable phase shifters in accordance with a fifth illustrative embodiment.

FIG. **16** depicts a plurality of tunable phase shifters in accordance with a sixth illustrative embodiment.

FIG. **17** depicts an equivalent circuit model of a tunable phase shifter of the plurality of tunable phase shifters of FIG. **16** in accordance with an illustrative embodiment.

FIG. **18** depicts a flow diagram illustrating examples of operations associated with designing any of the plurality of tunable phase shifters in accordance with an illustrative embodiment.

FIG. **19** depicts a block diagram of a transmitter design system in accordance with an illustrative embodiment.

FIG. **20** depicts a flow diagram illustrating examples of operations associated with determining a movement to steer a beam in accordance with an illustrative embodiment.

FIG. **21** depicts a block diagram of a beam steering control device in accordance with an illustrative embodiment.

FIG. **22** depicts a conductive antenna element as a dipole-type Jerusalem cross resonator in accordance with an illustrative embodiment.

FIG. **23** depicts an equivalent circuit model of a tunable phase shifter formed using the conductive antenna element of FIG. **22** in accordance with an illustrative embodiment.

FIG. **24** depicts a conductive antenna element as a slot-type Jerusalem cross resonator in accordance with an illustrative embodiment.

FIG. **25** depicts an equivalent circuit model of a tunable phase shifter formed using the conductive antenna element of FIG. **24** in accordance with an illustrative embodiment.

FIG. **26** depicts a perspective view of a second transmitter in accordance with an illustrative embodiment with laterally moving layers.

FIG. **27***a* depicts a magnitude of an electrical field distribution of the second transmitter of FIG. **26** in accordance with an illustrative embodiment.

FIG. **27***b* depicts a phase of the electrical field distribution of the second transmitter of FIG. **26** for three different lateral positions in accordance with an illustrative embodiment.

FIG. **28** depicts a perspective view of a third transmitter in accordance with an illustrative embodiment with rotating element.

FIG. **29***a* depicts a magnitude of an electrical field distribution of the third transmitter of FIG. **28** in accordance with an illustrative embodiment.

FIG. **29***b* depicts a phase of the electrical field distribution of the third transmitter of FIG. **28** for three different rotational positions in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

With reference to FIG. **1***a*, a side view of a tunable phase shifter **100** is shown in accordance with an illustrative embodiment. Tunable phase shifter **100** may include a spatial phase shift element **101** and a conducting sheet **108**. Spatial phase shift element **101** may include a dielectric substrate **104** and a conductive antenna element **102** mounted on dielectric substrate **104**. Dielectric substrate **104** is formed of a dielectric material having a thickness **110**, t. Dielectric substrate **104** is thin such that $t \ll \lambda_c$, where λ_c is a wavelength of operation. A spacer **106** may separate spatial phase shift element **101** from conducting sheet **108** to mount conducting sheet **108** a distance **112** from spatial phase shift element **101**. Spacer **106** may be filled with a dielectric material such as air. Spacer **106** may be formed by one or more walls (not shown) that support or make-up spatial phase shift element **101** and/or conducting sheet **108**. Distance **112** may be zero such that conducting sheet **108** approximately abuts dielectric substrate **104** in an illustrative embodiment.

As used herein, the term "mount" includes join, unite, connect, couple, associate, insert, hang, hold, affix, attach, fasten, bind, paste, secure, bolt, screw, rivet, solder, weld, glue, form over, form in, layer, mold, rest on, rest against, etch, abut, and other like terms. The phrases "mounted on", "mounted to", and equivalent phrases indicate any interior or exterior portion of the element referenced. These phrases also encompass direct mounting (in which the referenced elements are in direct contact) and indirect mounting (in which the referenced elements are not in direct contact, but are connected through an intermediate element). Elements referenced as mounted to each other herein may further be integrally formed together, for example, using a molding or thermoforming process as understood by a person of skill in the art. As a result, elements described herein as being mounted to each other need not be discrete structural elements. The elements may be mounted permanently, removably, or releasably unless specified otherwise.

An electromagnetic wave **118** received by spatial phase shift element **101** of tunable phase shifter **100** is reflected by conducting sheet **108** back through spatial phase shift element **101** resulting in a change in phase Φ_{var1} of a reflected electromagnetic wave **120** relative to electromagnetic wave **118**. For example, characteristics (such as the dimensions, the materials, the arrangement) of spatial phase shift element **101**, spacer **106**, and conducting sheet **108** are selected to generate a phase change Φ_{var1} when conducting sheet **108** is separated from spatial phase shift element **101** by distance **112** as discussed further below.

Referring to FIG. **1***b*, tunable phase shifter **100** is shown after movement of conducting sheet **108** to increase distance **112** by a second distance **114**. Conducting sheet **108** may be moved by a first actuator (not shown) mounted to move a first edge **124** the second distance **114** relative to spatial phase shift element **101** and by a second actuator (not shown) mounted to move a second edge **126** the second distance **114** relative to spatial phase shift element **101**. Electromagnetic wave **118** received by tunable phase shifter **100** is reflected by conducting sheet **108** back through spatial phase shift element **101** resulting in a change in phase Φ_{var2} of a second reflected electromagnetic wave **122** relative to electromagnetic wave **118**. Second distance **114** is selected to generate a differential phase change $\Phi_{var2}-\Phi_{var1}$ relative to the configuration shown in FIG. **1***a*.

An actuator may include an electric motor such as a brushed or brushless DC or AC motor, a servo motor, a stepper motor, a piezoelectric actuator, a pneumatic actuator, a gas motor, an induction motor, a gear motor, a harmonic, cable, worm, or other gear drive, a magnetic actuator, etc. The actuator may be used with or without sensors. The actuator may generate linear or rotating motion. As understood by a person of skill in the art, other mechanical devices such as gears may be incorporated to convert the motion generated by the actuator to move one or more portion of conducting sheet **108** as described.

Referring to FIG. **1***c*, tunable phase shifter **100** is shown after movement of conducting sheet **108** to increase distance **112** by a third distance **116**. Conducting sheet **108** may be moved by the first actuator mounted to move first edge **124** the third distance **116** relative to spatial phase shift element **101** and by the second actuator mounted to move second edge **126** the third distance **116** relative to spatial phase shift element **101**. Electromagnetic wave **118** received by tunable phase shifter **100** is reflected by conducting sheet **108** back through spatial phase shift element **101** resulting in a change in phase Φ_{var3} of a third reflected electromagnetic wave **128** relative to electromagnetic wave **118**. Third distance **116** is selected to generate a differential phase change $\Phi_{var3}-\Phi_{var1}$ relative to the configuration shown in FIG. **1***a*.

By moving conducting sheet **108** relative to spatial phase shift element **101**, the phase shift of the reflected electromagnetic wave can be changed. Of course, either or both of conducting sheet **108** and spatial phase shift element **101** can be moved relative to the other to generate a desired phase shift in the reflected electromagnetic wave that is radiated by tunable phase shifter **100**. The differential phase shift can be generated by moving conducting sheet **108** and spatial phase shift element **101** closer to each other or farther apart.

Conducting sheet **108** is a conducting surface with high conductivity that reflects received electromagnetic waves. Conducting sheet **108** is connected to a fixed potential that may be, but is not necessarily, a ground potential. Conducting sheet **108** may be generally flat or formed of ridges or bumps. Conducting sheet **108** may not be a continuous surface. Instead, conducting sheet **108** may be formed of separately movable sections. For illustration, conducting sheet **108** may be formed of a flexible membrane coated with a conductor.

Conductive antenna element **102** is formed of a conductive material having a high conductivity and may form a variety of shapes having a variety of dimensions (length, width, depth) based on the desired radiating characteristics of the radiated electromagnetic wave, such as first reflected electromagnetic wave **120**, second reflected electromagnetic wave **122**, and third reflected electromagnetic wave **128**, as discussed further below. For example, conductive antenna element **102** may be formed of a patch antenna element, a resonant dipole antenna element, a tri-pole antenna element, a Jerusalem cross antenna element, a split ring resonator antenna element, a multi-element dipole antenna element, etc.

Referring to FIG. **2***a*, tunable phase shifter **100** is shown after movement of only second edge **126** of conducting sheet **108** by an actuator to increase distance **112** by a fourth distance **200**. Fourth distance **200** is selected to generate the differential phase change $\Phi_{var2}-\Phi_{var1}$ based on the movement of conducting sheet **108** to the tilted position shown. An actuator may not be needed at first edge **124**.

Referring to FIG. **2***b*, tunable phase shifter **100** is shown after movement of only second edge **126** of conducting sheet **108** to increase distance **112** by a fifth distance **202**. Fifth distance **202** is selected to generate the differential phase change $\Phi_{var3}-\Phi_{var1}$ based on the movement of conducting sheet **108** to the second tilted position shown.

Referring to FIG. **2***c*, tunable phase shifter **100** is shown after movement of only second edge **126** of conducting sheet **108** to decrease distance **112** by a sixth distance **204**. Electromagnetic wave **118** received by tunable phase shifter **100** is reflected by conducting sheet **108** back through spatial phase shift element **101** resulting in a change in phase Φ_{var4} of a fourth reflected electromagnetic wave **206** relative to electromagnetic wave **118**. Sixth distance **204** is selected to generate a differential phase change $\Phi_{var4}-\Phi_{var1}$ relative to the configuration shown in FIG. **1***a* based on the movement of conducting sheet **108** to the third tilted position shown.

Referring to FIG. **3**, tunable phase shifter **100** is shown after movement of a center **300** of conducting sheet **108** by an actuator to increase distance **112** by a seventh distance **302**. Electromagnetic wave **118** received by tunable phase shifter **100** is reflected by conducting sheet **108** back through spatial phase shift element **101** resulting in a change in phase Φ_{var5} of a fifth reflected electromagnetic wave **304** relative to electromagnetic wave **118**. Seventh distance **302** is selected to generate a differential phase change $\Phi_{var5}-\Phi_{var1}$ relative to the configuration shown in FIG. **1***a* based on the movement of conducting sheet **108** to form a concave shape. Conducting sheet **108** may be formed of a flexible membrane that can be deflected at center **300**, at first edge **124**, and/or at second edge **126** under control of one or more actuators. Conducting sheet **108** may be anchored at first edge **124** and/or at second edge **126**. For example, if conducting sheet **108** has one anchor point at first edge **124**, conducting sheet **108** may be bent like a cantilever at second edge **126** to change a distance from spatial phase shift element **101**. For example, the separation distance between conducting sheet **108** and a bottom side of dielectric substrate **104** can be changed by changing an applied bias voltage to a piezoelectric actuator.

In its simplest form, conductive antenna element **102** includes a sub-wavelength capacitive patch placed on dielectric substrate **104**. Referring to FIG. **4**, an equivalent circuit model **400** of tunable phase shifter **100** with conductive antenna element **102** implemented as a sub-wavelength capacitive patch is shown in accordance with an illustrative embodiment. Equivalent circuit model **400** may include a capacitive element **402**, a first transmission line element **404**, a second transmission line element **406**, and a third transmission line element **408**. Capacitive element **402** may be associated with conductive antenna element **102** implemented as a sub-wavelength capacitive patch. First transmission line element **404** may be associated with a characteristic impedance Z_d resulting from thickness **110** selected for dielectric substrate **104**. Second transmission line element **406** may be associated with a characteristic impedance Z_0 resulting from distance **112** between conducting sheet **108** and a bottom of dielectric substrate **104**. Third transmission line element **408** may be short-circuited and associated with a characteristic impedance Z_v resulting from movement between conducting sheet **108** and spatial dielectric substrate **104** relative to distance **112**.

Referring to FIG. **5**, a simplified equivalent circuit model **500** of equivalent circuit model **400** is shown in accordance with an illustrative embodiment. The short-circuited first transmission line element **404**, second transmission line element **406**, and third transmission line element **408** have been combined into a single transmission line with a variable length that is short-circuited on one end. If the length of this short-circuited transmission line is less than a quarter wavelength, the single transmission line acts as a variable inductor **502**. Simplified equivalent circuit model **500** forms a parallel LC resonant circuit. To an incident electromagnetic wave, such as electromagnetic wave **118**, tunable phase shifter **100** acts as a distributed resonator where the capacitive patch acts as a capacitor of the parallel LC resonant circuit and dielectric substrate **104** backed by conducting sheet **108** forming a ground plane acts as variable inductor **502** of the parallel LC resonant circuit. At a frequency where the L and C resonate, the incident electromagnetic (EM) wave experiences a reflection coefficient of +1 (i.e., magnitude of 1 and a phase of 0 degrees). However, if the frequency of the incident EM wave is above or below the resonant frequency of the LC resonator, the reflection coefficient is $1\angle\phi$, where the magnitude of the reflection coefficient remains one, but the phase is ϕ so that tunable phase shifter **100** can be designed by changing variable inductor **502** and the resulting resonant frequency to provide a desired phase shift value at the selected frequency(ies) of operation. Thus, a frequency response of tunable phase shifter **100** can be changed by changing the value of the inductor, L. Specifically, when impedance Z_v is changed, the phase of the reflection coefficient is changed. The value of the inductor, L, can be changed by changing a distance between conducting sheet **108** and spatial phase shift element **101** relative to distance **112**.

Referring to FIG. **6**, a one-dimensional (1-D) side view of a transmitter **600** is shown in accordance with an illustrative embodiment. Transmitter **600** may include a feed antenna **602** and a plurality of tunable phase shifters **604**. As understood by a person of skill in the art, the wavelength of operation λ_c of transmitter **600** is defined as $\lambda_c = c/f_c$, where c is the speed of light and f_c is a carrier frequency. As an example, for $f_c \in [1, 15]$ Gigahertz (GHz), $\lambda_c \in [30,2]$ centimeters (cm).

Feed antenna **602** may have a low-gain. Feed antenna **602** may be a dipole antenna, a monopole antenna, a helical antenna, a microstrip antenna, a patch antenna, a fractal antenna, a feed horn, a slot antenna, an end fire antenna, a parabolic antenna, etc. Feed antenna **602** is positioned a focal distance **612**, f_d, from a front face **605** of the plurality of tunable phase shifters **604**. Feed antenna **602** is configured to receive an analog or digital signal, and in response, to radiate a spherical radio wave **606** toward front face **605** of the plurality of tunable phase shifters **604**.

In the illustrative embodiment of FIG. **6**, the plurality of tunable phase shifters **604** is distributed linearly in a vertical direction. The plurality of tunable phase shifters **604** include a plurality of conductive antenna elements **102** arranged on front face **605** and mounted on dielectric substrate **104**. Conductive sheet **108** is positioned on a back face **607** of the plurality of tunable phase shifters **604** that is opposite front face **605**. The plurality of tunable phase shifters **604** may be arranged to form a one-dimensional (1D) or a two-dimensional (2D) array of spatial phase shift elements in any direction. The plurality of tunable phase shifters **604** may form variously shaped apertures including circular, rectangular, square, elliptical, etc. The plurality of tunable phase shifters **604** can include any number of tunable phase shifters.

Each tunable phase shifter **100** of the plurality of tunable phase shifters **604** includes an embodiment of tunable phase shifter **100** structured to generate a defined phase shift on an incident electromagnetic wave. For example, referring to FIG. **8**, a perspective view of transmitter **600** is shown. Feed antenna **602** is illustrated as a feed horn. The plurality of tunable phase shifters **604** are arranged to form a circular 2D array of tunable phase shifters **100**. Each tunable phase shifter of the plurality of tunable phase shifters **604** may be designed to generate a different phase shift. The plurality of tunable phase shifters **604** has an aperture length **610**, D.

Though transmitter **600** is described as transmitting electromagnetic waves, as understood by a person of skill in the art, transmitter **600** may be a transceiver and configured to both send and receive electromagnetic waves. Additionally, a receiver system may use a similar architecture as that described with reference to transmitter **600** as understood by a person of skill in the art.

Referring again to FIG. **6**, as understood by a person of skill in the art, spherical radio wave **606** reaches different portions of front face **605** at different times. The plurality of tunable phase shifters **604** can be considered to be a plurality of pixels each of which act as a phase shift unit by providing a selected phase shift within the frequency band of interest. Thus, each tunable phase shifter **100** of the plurality of tunable phase shifters **604** acts as a phase shift circuit selected such that spherical radio wave **606** is re-radiated in the form of a planar wave **608** that is parallel to front face **605**. Given aperture length **610** and focal distance **612**, the phase shift profile provided for the plurality of tunable phase shifters **604** to form planar wave **608** can be calculated.

For example, assuming feed antenna **602** is aligned to emit spherical radio wave **606** at the focal point of the plurality of tunable phase shifters **604**, the time it takes for each ray to arrive at front face **605** is determined by a length of each ray trace, i.e., the distance traveled by the electromagnetic wave traveling at the speed of light. A minimum time corresponds to a propagation time of the shortest ray trace, which is the line path from feed antenna **602** to a center of front face **605**. A maximum time corresponds to a propagation time of the longest ray trace, which is the line path from feed antenna **602** to an edge of front face **605**. Feed antenna **602** may be positioned at an off-center position with a resulting change in the distribution of ray traces to each tunable phase shifter.

To achieve beam collimation and form planar wave **608**, each tunable phase shifter of the plurality of tunable phase shifters **604** provides a reverse phase shift profile. For example, referring to FIG. **7**, the plurality of tunable phase shifters **604** include a first tunable phase shifter **100*a***, a second tunable phase shifter **100*b***, a third tunable phase shifter **100*c***, and a fourth tunable phase shifter **100*d***. An embodiment of first tunable phase shifter **100*a*** is positioned at a top and a bottom of the plurality of tunable phase shifters **604**. An embodiment of second tunable phase shifter **100*b*** is positioned adjacent each embodiment of first tunable phase shifter **100*a***. An embodiment of third tunable phase shifter **100*c*** is positioned adjacent each embodiment of second tunable phase shifter **100*b*** on a side opposite first tunable phase shifter **100*a***. Fourth tunable phase shifter **100*d*** is positioned at a center of the plurality of tunable phase shifters **604** such that the plurality of tunable phase shifters **604** are arranged symmetrically from top to bottom.

As a result, a phase shift profile has a minimum value **706** at the top/bottom of front face **605**, and increases to a maximum value **700** at the center of the plurality of tunable phase shifters **604**. Thus, first tunable phase shifter **100*a*** generates minimum value **706** of phase shift based on the phase shift needed to collimate the received EM wave. Fourth tunable phase shifter **100*d*** generates maximum value **700** of phase shift based on the phase shift needed to collimate the received EM wave. Second tunable phase shifter **100*b*** generates a first intermediate value **704** of phase shift, and third tunable phase shifter **100*c*** generates a second intermediate value **702** of phase shift. Of course, the phase shift profile may be shifted based on a location of feed antenna **602** relative to front face **605** as understood by a person of skill in the art.

Referring to FIG. **9**, feed antenna **602** may be positioned off center relative to the plurality of tunable phase shifters **604**. Additionally, the phase shift profile implemented by each tunable phase shifter **100** of the plurality of tunable phase shifters **604** may be designed to radiate a high gain pencil beam **900** in a variable direction. In a 2D array such as that illustrated, the direction may vary in a horizontal direction **902** and in a vertical direction **904**.

Referring to FIG. **10**, if the tunable phase shifters **100** of the plurality of tunable phase shifters **604** are configured to provide a phase shift gradient over the aperture, planar wave **608** is directed towards an angle **1000**, θ, with respect to front face **605**. The radiated field of transmitter **600** is pointed towards a direction of 90−θ with respect to a vector normal to front face **605**. Because the response of the tunable phase shifters **100** is tunable, angle **1000** can be dynamically changed in horizontal direction **902** and/or in vertical direction **904**.

To achieve a radiated beam towards angle **1000**, two adjacent tunable phase shifters **100**, such as fourth tunable phase shifter **100***d* and a fifth tunable phase shifter **100***e*, have a relative phase shift of kd cos θ, where $k=2\pi/\lambda_c$ is a wavenumber and d is a spacing between the adjacent tunable phase shifters **100**. As discussed relative to FIGS. **1***a*-**1***c*, **2***a*-**2***c* and **3**, the phase shift of each tunable phase shifter **100** can be controlled by changing a distance between conducting sheet **108** relative to spatial phase shift element **101**. The tunable phase shifters **100** of the plurality of tunable phase shifters **604** locally manipulate the phase-front of the incident EM wave and convert spherical wave **606** radiated by feed antenna **602** to planar wave **608** pointed in direction θ.

The combination of feed antenna **602** and the plurality of tunable phase shifters **604** form a high-gain antenna. A direction of maximum radiation of the high-gain antenna is determined by the phase shift gradient of the electric field distribution over the aperture of the plurality of tunable phase shifters **604**. Because the phase shift gradient is dynamically changeable by changing the distance between conducting sheet **108** relative to spatial phase shift element **101**, the direction of maximum radiation of the antenna also changes. Such a dynamically reconfigurable system constitutes a beam steerable phased array.

Because the phase shift gradient over the aperture of the plurality of tunable phase shifters **604** is a continuous function, a simple continuous tiltable conducting sheet can be used to produce the phase shift gradient. For example, referring to FIG. **11**, a first plurality of tunable phase shifters **604***a* includes a first tunable phase shifter **100***a*, a second tunable phase shifter **100***b*, a third tunable phase shifter **100***c*, a fourth tunable phase shifter **100***d*, a fifth tunable phase shifter **100***e*, a sixth tunable phase shifter **100***f*, a seventh tunable phase shifter **100***g*, an eighth tunable phase shifter **100***h*, a ninth tunable phase shifter **100***i*, a tenth tunable phase shifter **100***j*, an eleventh tunable phase shifter **100***k*, a twelfth tunable phase shifter **100***l*, a thirteenth tunable phase shifter **100***m*, and a fourteenth tunable phase shifter **100***n*. The first plurality of tunable phase shifters **604***a* may be implemented in two dimensions though only one dimension is illustrated for simplicity.

First tunable phase shifter **100***a* includes a first conductive antenna element **102***a*; second tunable phase shifter **100***b* includes a second conductive antenna element **102***b*; third tunable phase shifter **100***c* includes a third conductive antenna element **102***c*; fourth tunable phase shifter **100***d* includes a fourth conductive antenna element **102***d*; fifth tunable phase shifter **100***e* includes a fifth conductive antenna element **102***e*; sixth tunable phase shifter **100***f* includes a sixth conductive antenna element **102***f*; seventh tunable phase shifter **100***g* includes a seventh conductive antenna element **102***g*; eighth tunable phase shifter **100***h* includes an eighth conductive antenna element **102***h*; ninth tunable phase shifter **100***i* includes a ninth conductive antenna element **102***i*; tenth tunable phase shifter **100***j* includes a tenth conductive antenna element **102***j*; eleventh tunable phase shifter **100***k* includes an eleventh conductive antenna element **102***k*; twelfth tunable phase shifter **100***l* includes a twelfth conductive antenna element **102***l*; thirteenth tunable phase shifter **100***m* includes a thirteenth conductive antenna element **102***m*; and fourteenth tunable phase shifter **100***n* includes a fourteenth conductive antenna element **102***n*.

Each conductive antenna element **102***a*-**102***n* is mounted on dielectric substrate **104**. For illustration, each conductive antenna element **102***a*-**102***n* may be a capacitive patch placed on the same dielectric substrate **104**. Each capacitive patch may have different dimensions to change a capacitive value of the capacitor of the parallel LC resonant circuit of simplified equivalent circuit model **500** to define a phase shift that varies across the aperture to create planar wave **608** that is parallel to front face **605** when conducting sheet **108** is positioned in line with the dashed line. Planar wave **608** defines a pencil beam in a direction of a normal vector **1106** that is normal to front face **605** conducting sheet **108** is positioned in line with the dashed line. Spacer **106** separates dielectric substrate **104** from conducting sheet **108** to mount conducting sheet **108** the distance **112** from dielectric substrate **104**. Conducting sheet **108** is continuous and common to each conductive antenna element **102***a*-**102***n*. Conducting sheet **108** has a first edge **1102** and a second edge **1104** opposite the first edge **1102**. First edge **1102** is an outside edge of conducting sheet **108** associated with first tunable phase shifter **100***a*. Second edge **1104** is an outside edge of conducting sheet **108** associated with fourteenth tunable phase shifter **100***n*.

In the illustrative embodiment of FIG. **11**, an actuator is mounted to second edge **1104** to tilt conducting sheet **108** a tilt distance **1100** relative to distance **112** at second edge **1104**. The distance between conducting sheet **108** and a bottom of dielectric substrate **104** varies continuously from distance **112** at first edge **1102** to distance **112** plus tilt distance **1100** at second edge **1104** thereby producing a phase shift gradient that radiates planar wave **608** at angle **1000** with respect to normal vector **1106**. By adjusting tilt distance **1100**, angle **1000** can be changed to steer planar wave **608** in a specific direction thereby allowing electronic beam steering.

A phase shift gradient is created that results in a maximum phase shift provided by first tunable phase shifter **100***a*, and a minimum phase shift provided by fourteenth tunable phase shifter **100***n*. The phase shift gradient is approximately continuous over the aperture. As a result, an approximately continuous phase shift is created. The direction of maximum radiation can be dynamically changed by changing a direction and a magnitude of the phase shift gradient by adjusting the slope of conducting sheet **108**.

As another example, referring to FIG. **12**, a second plurality of tunable phase shifters **604***b* is shown in accordance with an illustrative embodiment. The second plurality of tunable phase shifters **604***b* differs from the first plurality of tunable phase shifters **604***a* in that conducting sheet **108** is discontinuous at each edge of each tunable phase shifter **100***a*-**100***n*. The second plurality of tunable phase shifters **604***b* can be made individually tunable by changing the distance to their respective ground planes (conducting sheets) individually. Conducting sheet **108** is divided into a plurality of sections that are independently moveable with one section for each tunable phase shifter **100**. First tunable phase shifter **100***a* includes a first conducting sheet element **108***a*; second tunable phase shifter **100***b* includes a second conducting sheet element **108***b*; third tunable phase shifter **100***c* includes a third conducting sheet element **108***c*; fourth tunable phase shifter **100***d* includes a fourth conducting sheet element **108***d*; fifth tunable phase shifter **100***e* includes a fifth conducting sheet element **108***e*; sixth tunable phase shifter **100***f* includes a sixth conducting sheet element **108***f*; seventh tunable phase shifter **100***g* includes a seventh conducting sheet element **108***g*; eighth tunable phase shifter **100***h* includes an eighth conducting sheet element **108***h*; ninth tunable phase shifter **100***i* includes a ninth conducting sheet element **108***i*; tenth tunable phase shifter **100***j* includes a tenth conducting sheet element **108***j*; eleventh tunable phase shifter **100***k* includes an eleventh conducting sheet element **108***k*; twelfth tunable phase shifter **100***l* includes a twelfth conducting sheet element **108***l*; thirteenth tunable phase shifter **100***m* includes a thirteenth conducting sheet element **108***m*; and fourteenth tunable phase shifter **100***n* includes a fourteenth conducting sheet element **108***n*.

First edge **1102** is an outside edge of first conducting sheet element **108***a* associated with first tunable phase shifter **100***a*. Second edge **1104** is an outside edge of fourteenth conducting sheet element **108***n* associated with fourteenth tunable phase shifter **100***n*. In the illustrative embodiment of FIG. **12**, an actuator may be mounted to each edge of each conducting sheet element **108***a*-**108***n* to provide a stepped slope of conducting sheet **108** to an overall tilt distance **1200** relative to distance **112** at second edge **1104**. Of course, first conducting sheet element **108***a* may not need actuators if it is not moved. The distance between conducting sheet **108** and a bottom of dielectric substrate **104** varies in steps from distance **112** at first edge **1102** to distance **112** plus overall tilt distance **1200** at second edge **1104** thereby producing a phase shift gradient that radiates planar wave **608** at angle **1000** with respect to normal vector **1106**. By adjusting individual distances between each conducting sheet element **108***a*-**108***n* and dielectric substrate **104** to achieve overall tilt distance **1200** at fourteenth conducting sheet element **108***n*, angle **1000** can be changed to steer planar wave **608** in a specific direction thereby allowing electronic beam steering. Again, a phase shift gradient is created that results in a maximum phase shift provided by first tunable phase shifter **100***a*, and a minimum phase shift provided by fourteenth tunable phase shifter **100***n*. The direction of maximum radiation can be dynamically changed by changing a direction and a magnitude of the phase shift gradient by adjusting the slope of conducting sheet **108**.

As yet another example, referring to FIG. **13**, a third plurality of tunable phase shifters **604***c* is shown in accordance with an illustrative embodiment. The third plurality of tunable phase shifters **604***c* differs from the second plurality of tunable phase shifters **604***b* in that conducting sheet **108** is discontinuous though not at each edge of each tunable phase shifter **100***a*-**100***n*. Conducting sheet **108** is divided into a plurality of sections that are independently moveable with one section for one or more tunable phase shifters **100**. For example, first tunable phase shifter **100***a*, second tunable phase shifter **100***b*, and third tunable phase shifter **100***c* include a first conducting sheet element **108'**; fourth tunable phase shifter **100***d* and fifth tunable phase shifter **100***e* include a second conducting sheet element **108"**; sixth tunable phase shifter **100***f* and seventh tunable phase shifter **100***g* include a third conducting sheet element **108'"**; eighth tunable phase shifter **100***h* and ninth tunable phase shifter **100***i* include a third conducting sheet element **108""**; whereas, tenth tunable phase shifter **100***j* includes tenth conducting sheet element **108***j*; eleventh tunable phase shifter **100***k* includes eleventh conducting sheet element **108***k*; twelfth tunable phase shifter **100***l* includes twelfth conducting sheet element **108***l*; thirteenth tunable phase shifter **100***m* includes thirteenth conducting sheet element **108***m*; and fourteenth tunable phase shifter **100***n* includes fourteenth conducting sheet element **108***n*. The third plurality of tunable phase shifters **604***c* can be made tunable in sections by changing the distance to their respective ground planes (conducting sheets) as a section.

In the illustrative embodiment of FIG. **13**, an actuator may be mounted to each edge of each conducting sheet element **108'**, **108"**, **108'"**, **108""**, **108***j*-**108***n* to provide a stepped slope of conducting sheet **108** to overall tilt distance **1200** relative to distance **112** at second edge **1104**. Thus, overall tilt distance **1200** at fourteenth conducting sheet element **108***n* is achieved with fewer step changes between first edge **1102** and second edge **1104**. Of course, tunable phase shifters **100***a*-**100***n* may be grouped in other manners. Again, a phase shift gradient is created that results in a maximum phase shift provided by first tunable phase shifter **100***a*, and a minimum phase shift provided by fourteenth tunable phase shifter **100***n*. The direction of maximum radiation can be dynamically changed by changing a direction and a magnitude of the phase shift gradient by adjusting the slope of conducting sheet **108**.

As still another example, referring to FIG. **14**, a second transmitter **600***a* is shown in accordance with an illustrative embodiment. Second transmitter **600***a* includes a second feed antenna **1400** and a fourth plurality of tunable phase shifters **604***d*. Second feed antenna **1400** may support surface wave propagation. For example, second feed antenna **1400** may be implemented as a leaky wave antenna. Second feed antenna **1400** may include a patch antenna **1402**, an inner conductor **1404** of coaxial cable, and an outer conductor **1406** of the coaxial cable. Inner conductor **1404** is electrically connected to feed patch antenna **1402**. Outer conductor **1406** is electrically connected to conducting sheet **108**, which may be grounded. For illustration, patch antenna **1402** may be formed of metallic patterns printed on a periodic structure. The metallic patterns can be as simple as rectangular or elliptical metallic patches or more complicated structures such as dipoles, tri-poles, split-ring resonators, etc.

The fourth plurality of tunable phase shifters **604***d* include a plurality of spatial phase shift elements **101***a*-**101***n*, spacer **106**, and conducting sheet **108**. The plurality of spatial phase shift elements **101***a*-**101***n* may include dielectric substrate **104**, top conductive antenna elements **102***a*-**102***n*, and bottom conductive antenna elements **1410***a*-**1410***n*. Each of the top conductive antenna elements **102***a*-**102***n* and each of the bottom conductive antenna elements **1410***a*-**1410***n* are mounted on dielectric substrate **104**. For example, a first spatial phase shift element **101***a* includes a first top conductive antenna element **102***a* and a first bottom conductive antenna element **1410***a*. First top conductive antenna element **102***a* is mounted on a top surface of dielectric substrate **104** to form a portion of front face **605**, and first bottom conductive antenna element **1410***a* is mounted on a bottom surface of dielectric substrate **104**. Spacer **106** is positioned between bottom conductive antenna element **1410***a* and conducting sheet **108**. Similarly, second top conductive antenna element **102***b* is mounted on the top surface of dielectric substrate **104**, and second bottom conductive antenna element **1410***b* is mounted on the bottom surface of dielectric substrate **104**; third top conductive antenna element **102***c* is mounted on the top surface of dielectric substrate **104**, and third bottom conductive antenna element **1410***c* is mounted on the bottom surface of dielectric substrate **104**, . . . , and fourteenth top conductive antenna element **102***n* is mounted on the top surface of dielectric substrate **104**, and fourteenth bottom conductive antenna element **1410***n* is mounted on the bottom surface of dielectric substrate **104**.

Patch antenna **1402** is positioned within spacer **106**. As a surface wave **1408** propagates from patch antenna **1402**, surface wave **1408** radiates (leaks) into the space within spacer **106**. Surface wave **1408** excites a second surface wave that propagates from second transmitter **600***a*. Second transmitter **600***a* forms a traveling wave antenna where a direction of maximum radiation of the antenna is determined by a propagation constant of the second surface wave. This direction can be changed by dynamically tuning the parameters of the surface waveguide formed by the fourth plurality of tunable phase shifters **604***d*. For example, referring to FIG. **15**, the propagation constant of the surface waveguide can be changed by changing a separation between conducting sheet **108** and the plurality of spatial phase shift elements **101**. For example, a first corner **1504** may be separated a first corner distance **1506** from the bottom surface of dielectric substrate **104**, a second corner **1508** may be separated a second corner distance **1510** from the bottom surface of dielectric substrate **104**, and a third corner **1512** may be separated a third corner distance **1514** from the bottom surface of dielectric substrate **104**. A fourth corner (not shown) may be fixed at distance **112**. A first actuator (not shown) may be mounted to adjust first corner distance **1506**, a second actuator (not shown) may be mounted to adjust second corner distance **1510**, and a third actuator (not shown) may be mounted to adjust third corner distance **1514**. Again, a phase shift gradient is created that results in a maximum phase shift provided by first spatial phase shift element **101***a*, and a minimum phase shift provided by fourteenth spatial phase shift element **101***n*. The direction of maximum radiation can be dynamically changed by changing a direction and a magnitude of the phase shift gradient by adjusting the slope of conducting sheet **108**. In alternative embodiments, conducting sheet **108** may be formed of independently movable sections as discussed with reference to FIGS. **12** and **13**.

More complicated conductive antenna elements may be used for tunable phase shifter **100**. For example, with reference to FIG. **16**, a fifth plurality of spatial phase shift elements **1600** is shown in accordance with an illustrative embodiment. In the illustrative embodiment, the spatial phase shift elements **1600** form a 2D rectangular array of 49 spatial phase shift elements. The rectangular array has a width **1602** in an x-direction, a height **1604** in a y-direction, and a depth **1606** in a z-direction. Each spatial phase shift element may be formed of one or more layers of material. For example, spatial phase shift element **101** of FIG. **1***a* is formed of two layers, dielectric substrate **104** and conductive antenna element **102**. As another example, spatial phase shift element **101***a* of FIG. **14** is formed of three layers, first top conductive antenna element **102***a*, dielectric substrate **104**, and first bottom conductive antenna element **1410***a*.

In an alternative embodiment, each spatial phase shift element may be formed of a greater number of layers of material. For example, referring to FIG. **16**, a spatial phase shift element **1608** includes a first capacitive patch **1610** mounted on a first dielectric patch **1612**, a second capacitive patch **1614** mounted between first dielectric patch **1612** and a second dielectric patch **1616**, a third capacitive patch **1618** mounted between second dielectric patch **1616** and a third dielectric patch **1620**, and a fourth capacitive patch **1622** mounted on third dielectric patch **1620** on a side opposite third capacitive patch **1618**. Spatial phase shift element **1608** has an element width **1624** in the x-direction, an element height **1626** in the y-direction, and depth **1606** in the z-direction. Element width **1624** and element height **1626** are typically less than a minimum λ_c defined for the frequency band of interest. Spatial phase shift element **1608** forms a multi-layered frequency selective surface composed of a number of closely spaced metallic layers separated from one another by dielectric substrates. For example, spatial phase shift element **1608** may be formed by bonding different dielectric substrates together using a bonding film such as a prepreg, which is a reinforcement material pre-impregnated with a polymer or resin matrix in a controlled ratio. Thermosetting polymers/resins solidify by cross-linking to create a permanent network of polymer chains as understood by a person of skill in the art. The dielectric substrates may form a flexible membrane that can be deflected or bent in a manner similar to that described with reference to conducting sheet **108** to allow the dielectric substrate to be moved instead of or in addition to movement of conducting sheet **108**.

As discussed above, each spatial phase shift element of the plurality of spatial phase shift elements **1600** forms a phase shift circuit at each grid position based on the selected arrangement of capacitive patch layers and dielectric sheet layers. For example, with reference to FIG. **17**, an equivalent circuit **1700** for spatial phase shift element **1608** is shown in accordance with an illustrative embodiment. Equivalent circuit **1700** includes a first capacitor C_1 associated with a capacitance created by first capacitive patch **1610**, a second capacitor C_2 associated with a capacitance created by second capacitive patch **1614**, a third capacitor C_3 associated with a capacitance created by third capacitive patch **1618**, and a fourth capacitor C_4 associated with a capacitance created by fourth capacitive patch **1622** arranged in parallel as shunt capacitors.

Equivalent circuit **1700** further includes a first transmission line with characteristic impedance Z_1 and length h_1 associated with first dielectric patch **1612**, a second transmission line with characteristic impedance Z_2 and length h_2 associated with second dielectric patch **1616**, and a third transmission line with characteristic impedance Z_3 and length h_3 associated with third dielectric patch **1620** arranged in series between the shunt capacitors associated with the adjacent capacitive patch(es). Thus, equivalent circuit **1700** acts as a low pass filter that is implemented by each spatial phase shift element of the plurality of spatial phase shift elements **1600**. More specifically, equivalent circuit **1700** acts as a 7th order low pass filter as a result of the number of capacitive patch layers, four, and dielectric sheet layers, three, that form each spatial phase shift element. Equivalent circuit **1700** may replace capacitive element **402** of simplified equivalent circuit **500** of FIG. **5** to design tunable phase shifter **100**.

To achieve different phase shifts over the desired frequency range, the plurality of spatial phase shift elements **1600** can be designed to have linear transmission phases with different slopes. The steeper the slope of the transmission phase, the larger the phase shift it will provide. The group delay is determined by several factors including both the order of the filter and the fractional bandwidth.

With reference to FIG. **18**, operations associated with designing any of the plurality of tunable phase shifters **604**, **604***a*, **604***b*, **604***c*, **604***d*, **1600** are described in accordance with an illustrative embodiment. The operations may be performed by a transmitter design application **1918** shown with reference to FIG. **19**. Additional, fewer, or different operations may be performed depending on the embodiment. The order of presentation of the operations of FIG. **18** is not intended to be limiting. Thus, although some of the operational flows are presented in sequence, the various operations may be performed in various repetitions, concurrently, and/or in other orders than those that are illustrated.

For example, transmitter **600** shown with reference to FIG. **8** may be designed. The plurality of tunable phase shifters **604** is assumed to be located in an x-y plane. For illustration, the plurality of tunable phase shifters may be further assumed to have a circular aperture with a diameter of D equal to aperture length **610**. The travel time it takes for the wave originated at feed antenna **602** to arrive at an arbitrary point on front face **605** of the plurality of tunable phase shifters with coordinates (x, y, z=0) is calculated as:

$$T(x,y,z=0)=\sqrt{x^2+y^2+f_d^2}/c$$

where $0<\sqrt{x^2+y^2}<D/2$ and f_d is focal distance **612** between feed antenna **102** and the plurality of tunable phase shifters **604**. The time delay profile that needs to be provided by the plurality of tunable phase shifters **604** can be calculated as:

$$TD(x,y,z=h)=(\sqrt{(D/2)^2+f_d^2}-r)/c+t_0 \quad (1)$$

where $r=\sqrt{x^2+y^2+f_d^2}$ and $t_0\geq 0$ is an arbitrary constant, which represents a constant time delay added to the response of each tunable phase shifter of the plurality of tunable phase shifters **604**. The phase profile at the operating frequency can be calculated from:

$$\Phi(x,y)=k(\sqrt{(D/2)^2+f_d^2}-r)+\Phi_0 \quad (2)$$

where Φ_0 is a positive constant that represents a constant phase delay added to the response of each tunable phase shifter of the plurality of tunable phase shifters **604** and $r=\sqrt{x^2+y^2+f_d^2}$ is the distance between an arbitrary tunable phase shifter specified by its coordinates (x, y, z=0) and feed antenna **102** (x=0, y=0, z=f_d).

To ensure that front face **605** of the plurality of tunable phase shifters **604** represents an equal phase and an equal delay surface, two conditions are satisfied across the aperture. First, the time delay profile provided for each tunable phase shifter calculated from equation (1) is approximately the same over the desired band of operation. Second, the phase shift profile at the operating frequency is approximately equal to that calculated from equation (2). Satisfying these two conditions ensures that the signal carried by the incident wave is not distorted. Moreover, it ensures that planar wave **608** at the output of the plurality of tunable phase shifters **604** is spatially coherent over the desired frequency range. Equation (1) is essentially the negative derivative of equation (2) with respect to the frequency, which is expected since, by definition, the group delay is defined as the negative derivative of the phase with respect to the frequency. Therefore, satisfying the phase condition in equation (2) at each frequency point within the desired frequency range automatically leads to the satisfaction of equation (1).

With reference to FIG. **18**, in an operation **1800**, a desired center frequency of operation is received. For example, a user may execute transmitter design application **1918** which causes presentation of a first user interface window, which may include a plurality of menus and selectors such as drop down menus, buttons, text boxes, hyperlinks, additional windows, etc. associated with transmitter design application **1918**. The user, for example, may enter the frequency into a text box or select the frequency from a drop down menu. As understood by a person of skill in the art, the first user interface window is presented on a display **1914** (shown with reference to FIG. **19**) under control of the computer-readable and/or computer-executable instructions of transmitter design application **1918** executed by a processor **1908** (shown with reference to FIG. **19**) of a transmitter design system **1900** (shown with reference to FIG. **19**). As the user interacts with the first user interface presented by transmitter design application **1918**, different user interface windows may be presented to provide the user with more or less detailed information related to designing transmitter **600**. Thus, as known to a person of skill in the art, transmitter design application **1918** receives an indicator associated with an interaction by the user with a user interface window presented under control of transmitter design application **1918**. Based on the received indicator, transmitter design application **1918** performs one or more operations.

In an operation **1802**, values for the characteristics of feed antenna **602** are received. For example, a type of feed element, a directivity, a half power beam width, a tapering, etc. may be selected or entered by a user.

In an operation **1804**, an operational bandwidth for transmitter **600** is received. For example, the user may enter the bandwidth into a text box or select the bandwidth from a drop down menu. In an operation **1806**, a desired size of the aperture of the plurality of tunable phase shifters **604** and a desired focal distance f_d are received. For example, when the plurality of tunable phase shifters **604** are arranged in a circular shape, the user may enter the diameter D into a text box or select the diameter D from a drop down menu. The user also may enter the focal distance f_d into a text box or select the focal distance f_d from a drop down menu.

These parameters may be determined from practical design consideration such as a 3 dB beamwidth, an available volume for transmitter **600**, and a maximum tolerable thickness depth of the plurality of tunable phase shifters **604**. Another factor in choosing these parameters is a trade-off between a spillover loss and an aperture efficiency. To increase the efficiency of transmitter **600**, spillover loss should be minimized. Spillover loss, however, is a function of a radiation pattern of feed antenna **602** and the f_d/D ratio. For a given feed antenna **602**, spillover loss can be reduced by reducing the f_d/D ratio while ensuring the tapering over the aperture caused by this does not significantly decrease the aperture efficiency. A maximum bandwidth of transmitter **600** may be primarily limited by the bandwidth of feed antenna **602**.

To define the time delay for each tunable phase shifter **100** of the plurality of tunable phase shifters **604**, the aperture may be divided into M concentric zones with identical tunable phase shifters **100** populated within each zone. In an operation **1808**, a number of discrete regions or zones into which to divide the aperture of the plurality of tunable phase shifters **604** is received. For example, the user may enter the number of zones into a text box or select the number of zones from a drop down menu. In general, the number of zones may be selected to provide a phase shift profile with as much continuity as possible, which in turn results in phase shift elements that are as small as possible compared to the wavelength band of interest.

In an operation **1810**, a time delay and phase delay profile is determined for each zone using equations (3) and (4), respectively, below:

$$TD(x_m,y_m)=(\sqrt{(D/2)^2+f_d^2}-r_m)/c+t_0 \quad (3)$$

$$\Phi(x_m,y_m)=k_0(\sqrt{(D/2)^2+f_d^2}-r_m)+\Phi_0 \quad (4)$$

where $r_m=\sqrt{x_m^2+y_m^2+f_d^2}$, and where x_m, y_m are the distances to the center of each zone and where m=0, 1, . . . , M−1.

The number of capacitive patch layers and dielectric sheet layers that form each tunable phase shifter **100** may be selected based on a filter order selected to achieve the maximum phase shift. In an operation **1812**, a desired filter order for each tunable phase shifter **100** is received. For example, the user may enter the filter order into a text box or select the filter order from a drop down menu. Alternatively, transmitter design application **1918** may automatically calculate the filter order of each tunable phase shifter **100** based on a maximum time delay and phase delay.

The phase shift provided by each tunable phase shifter **100** is a function of the order of the filter and its bandwidth. Decreasing the bandwidth of the filter or increasing the order of the filter increases the phase shift achievable from it. In this design application, the phase shift and the bandwidth are known. Microwave filter design handbooks typically have tables and figures that show group delay responses of standard low-pass filters with different response types and orders. Once the required phase shift from each tunable phase shifter **100** and the desired bandwidth are determined, the minimum order of the filter that provides the required maximum phase shift can be determined by checking these standard filter responses. Any order higher than this minimum order also satisfies the response for the transmitter design. Alternatively, the filter order can be determined using computer simulations of simplified equivalent circuit model **500**. The order of the filter can initially be estimated and the response of the simplified equivalent circuit model **500** simulated based on the estimate. Based on the simulated response, the order of the filter can be increased or decreased as necessary and the simulation process repeated to obtain the exact minimum order of the filter that provides a desired group delay. The number of dielectric sheet layers used to form each tunable phase shifter **100** of the plurality of tunable phase shifters **604** is defined as the desired filter order minus one and divided by two.

In an operation **1814**, the equivalent circuit capacitance and transmission line and length values are defined to achieve the maximum phase shift profile defined for the associated tunable phase shifter **100** of the plurality of tunable phase shifters **604** given the desired filter order. In an operation **1816**, the characteristics of dielectric substrate **104**, spacer **106**, conductive antenna element **102**, and distance **112** of a tunable phase shifter **100** of the center pixel is calculated to provide a linear transmission phase with the steepest slope (or largest time delay) over the selected operational bandwidth. In an operation **1818**, the equivalent circuit capacitance and transmission line impedance, and length values are defined to achieve the time delay and phase delay profile defined for each zone in equations (3) and (4), respectively, given the desired filter order.

In an operation **1820**, the characteristics of dielectric substrate **104**, spacer **106**, conductive antenna element **102**, and distance **112** of a tunable phase shifter **100** in each zone are calculated to provide the time delay and phase delay profile defined for each zone in equations (3) and (4), respectively. For example, this design process can be accomplished following well-known microwave filter design techniques and with the aid of computer aided design (CAD) tools to simulate the response of the equivalent circuit model **500** to ensure that the desired phase response is achieved. The dimensions of each tunable phase shifter **100** may be optimized using a full-wave EM simulation.

With reference to FIG. **19**, a block diagram of transmitter design system **1900** is shown in accordance with an illustrative embodiment. Transmitter design system **1900** may be a computing device of any form factor such as a personal digital assistant, a desktop, a laptop, an integrated messaging device, a smart phone, a tablet computer, etc. In an illustrative embodiment, transmitter design system **1900** may include an input interface **1902**, an output interface **1904**, a computer-readable medium **1906**, and a processor **1908**. Fewer, different, and additional components may be incorporated into transmitter design system **1900**.

Input interface **1902** provides an interface for receiving information from the user for entry into transmitter design system **1900** as known to those skilled in the art. Input interface **1902** may interface with various input technologies including, but not limited to, a mouse **1910**, a keyboard **1912**, display **1914**, a track ball, a keypad, one or more buttons, etc. to allow the user to enter information into transmitter design system **1900** or to make selections presented in a user interface displayed on display **1914**. The same interface may support both input interface **1902** and output interface **1904**. For example, display **1914** comprising a touch screen both allows user input and presents output to the user. Transmitter design system **1900** may have one or more input interfaces that use the same or a different input interface technology. The input devices further may be accessible by transmitter design system **1900** through a communication interface (not shown).

Output interface **1904** provides an interface for outputting information for review by a user of transmitter design system **1900**. For example, output interface **1904** may interface with various output technologies including, but not limited to, display **1914**, a printer, etc. Transmitter design system **1900** may have one or more output interfaces that use the same or a different interface technology. The output devices further may be accessible by transmitter design system **1900** through the communication interface.

Computer-readable medium **1906** is an electronic holding place or storage for information so that the information can be accessed by processor **1908** as known to those skilled in the art. Computer-readable medium **1906** can include, but is not limited to, any type of random access memory (RAM), any type of read only memory (ROM), any type of flash memory, etc. such as magnetic storage devices (e.g., hard disk, floppy disk, magnetic strips, . . .), optical disks (e.g., CD, DVD, . . .), smart cards, flash memory devices, etc. Transmitter design system **1900** may have one or more computer-readable media that use the same or a different memory media technology. Transmitter design system **1900** also may have one or more drives that support the loading of a memory media such as a CD or DVD, an external hard drive, etc.

Processor **1908** executes instructions as understood by those skilled in the art. The instructions may be carried out by a special purpose computer, logic circuits, or hardware circuits. Processor **1908** may be implemented in hardware and/or firmware. Processor **1908** executes an instruction, meaning it performs/controls the operations called for by that instruction. The term "execution" is the process of running an application or the carrying out of the operation called for by an instruction. The instructions may be written using one or more programming language, scripting language, assembly language, etc. Processor **1908** operably couples with input interface **1902**, with output interface **1904**, and with computer-readable medium **1906** to receive, to send, and to process information. Processor **1908** may retrieve a set of instructions from a permanent memory device and copy the instructions in an executable form to a temporary memory device that is generally some form of RAM.

Transmitter design application **1918** performs operations associated with designing transmitter **600**. For example, transmitter design application **1918** is configured to perform one or more of the operations described with reference to FIG. **18**. The operations may be implemented using hardware, firmware, software, or any combination of these methods. With reference to the example embodiment of FIG. **19**, transmitter design application **1918** is implemented in software (comprised of computer-readable and/or computer-executable instructions) stored in computer-readable medium **1906** and accessible by processor **1908** for execution of the instructions that embody the operations of transmitter design application **1918**. Transmitter design application **1918** may be written using one or more programming languages, assembly languages, scripting languages, etc. Transmitter design application **1918** may be implemented as a Web application.

With reference to FIG. **20**, operations associated with determining a movement by one or more actuators **2112** (shown with reference to FIG. **21**) to steer a beam radiated by transmitter **600** to a specific angle are described in accordance with an illustrative embodiment. For example, the one or more actuators **2112** are mounted to move conducting sheet **108** (or its sections) relative to spatial phase shift elements **101** to adjust a phase shift gradient. The operations may be performed by a beam steering control application **2110** shown with reference to FIG. **21**. Additional, fewer, or different operations may be performed depending on the embodiment. The order of presentation of the operations of FIG. **20** is not intended to be limiting. Thus, although some of the operational flows are presented in sequence, the various operations may be performed in various repetitions, concurrently, and/or in other orders than those that are illustrated.

In an operation **2000**, an indicator of a steering angle is received. For example, a receiver or target is located at a known steering angle relative to normal vector **1106**.

In an operation **2002**, a height of conductive sheet **108** is computed for one or more edges of conductive sheet **108** based on the phase shift gradient needed to steer the beam to the received steering angle.

In an operation **2004**, an actuator command is computed to move the one or more edges of conductive sheet **108** to the computed height.

With reference to FIG. **21**, a block diagram of beam steering control device **2100** is shown in accordance with an illustrative embodiment. Beam steering control device **2100** may be a computing device of any form factor. In an illustrative embodiment, beam steering control system **2100** may include a second input interface **2102**, a second output interface **2104**, a second computer-readable medium **2106**, a second processor **2108**, beam steering control application **2110**, and the one or more actuators **2112**. Fewer, different, and additional components may be incorporated into beam steering control device **2100**.

Second input interface **2102** provides the same or similar functionality as that described with reference to input interface **1902** though referring to beam steering control device **2100**. Second output interface **2104** provides the same or similar functionality as that described with reference to output interface **1904** though referring to beam steering control device **2100**. Second output interface **2104** also interfaces with the one or more actuators **2112** to provide the actuator command to each of the one or more actuators **2112**. Second computer-readable medium **2106** provides the same or similar functionality as that described with reference to computer-readable medium **1906** though referring to beam steering control device **2100**. Second processor **2108** provides the same or similar functionality as that described with reference to processor **1908** though referring to beam steering control device **2100**.

Beam steering control application **2110** performs operations associated with determining a movement by the one or more actuators **2112** to steer a beam radiated by transmitter **600** to a specific angle. For example, beam steering control application **2110** is configured to perform one or more of the operations described with reference to FIG. **20**. The operations may be implemented using hardware, firmware, software, or any combination of these methods. With reference to the example embodiment of FIG. **21**, beam steering control application **2110** is implemented in software (comprised of computer-readable and/or computer-executable instructions) stored in second computer-readable medium **2106** and accessible by second processor **2108** for execution of the instructions that embody the operations of beam steering control application **2110**. Beam steering control application **2110** may be written using one or more programming languages, assembly languages, scripting languages, etc.

Conductive antenna element **102** can assume other shapes and architectures. For example, instead of non-resonant rectangular patches, resonant dipole antennas, tri-poles, Jerusalem crosses, or split ring resonators may be used. For example, referring to FIG. **22**, conductive antenna element **102** is illustrated as a dipole-type Jerusalem cross resonator **2200** placed on dielectric substrate **104**. Referring to FIG. **23**, an equivalent circuit model **2300** of tunable phase shifter **100** with conductive antenna element **102** implemented as dipole-type Jerusalem cross resonator **2200** is shown in accordance with an illustrative embodiment. Equivalent circuit model **2300** may include capacitive element **402**, an inductive element **2302**, first transmission line element **404**, second transmission line element **406**, and third transmission line element **408**. At its first resonance, dipole-type Jerusalem cross resonator **2200** (or any dipole resonator type) has an equivalent circuit model of a series LC. As a result, inductive element **2302** is in series with capacitive element **402** to represent the electrical effect of conductive antenna element **102** implemented as dipole-type Jerusalem cross resonator **2200**. Capacitive element **402** may be tunable as well.

As another example, referring to FIG. **24**, conductive antenna element **102** is illustrated as a slot-type Jerusalem cross resonator **2400** placed on dielectric substrate **104**. Referring to FIG. **25**, an equivalent circuit model **2500** of tunable phase shifter **100** with conductive antenna element **102** implemented as slot-type Jerusalem cross resonator **2400** is shown in accordance with an illustrative embodiment. Equivalent circuit model **2500** may include capacitive element **402**, a second inductive element **2502**, first transmission line element **404**, second transmission line element **406**, and third transmission line element **408**. At its first resonance, slot-type Jerusalem cross resonator **2400** has an equivalent circuit model of a parallel LC. As a result, second inductive element **2502** is in parallel with capacitive element **402** to represent the electrical effect of conductive antenna element **102** implemented as slot-type Jerusalem cross resonator **2400**. Capacitive element **402** may be tunable as well.

In addition to the architectures presented previously, other types of mechanical movements can also be used to perform beam steering. For example, referring to FIG. **26**, a lateral movement is shown between layers of a multi-layer periodic structure. In alternative embodiments, a greater number of layers may be used. Referring to FIG. **26**, a perspective view of a transmitter **2602** is shown. Transmitter **2602** may include feed antenna **602** (not shown) and an aperture **2604**. Aperture **2604** may be formed of a bottom metal layer (not shown), a top metal layer **2606**, a top dielectric layer **2608**, a middle metal layer **2610**, and a bottom dielectric layer **2612**. Top metal layer **2606** is formed on top dielectric layer **2608** to form a first periodic arrangement of sub-wavelength capacitive patches. Middle metal layer **2610** is formed on bottom dielectric layer **2612** to form a second periodic arrangement of sub-wavelength capacitive patches. The bottom metal layer may be a continuous ground plane positioned on a side of bottom dielectric layer **2612** opposite middle metal layer **2610**. In one direction, the first and second periodic arrangements of sub-wavelength capacitive patches are identical, and in the other direction, the dimensions of the patches change gradually as one moves away from one edge of aperture **2604** to an opposite edge. Aperture **2604** behaves as a reflect array antenna when illuminated with incident wave **2613** generated by and radiated from feed antenna **602**. In the illustrative embodiment of FIG. **26**, incident wave **2613** is shown to be incident from the direction normal to aperture **2604**. A phase shift gradient provided by the distribution of the first and second periodic arrangements of sub-wavelength capacitive patches over aperture **2604** determines a direction of the radiated beam. As one of the layers of capacitive patches is moved with respect to the other, the phase shift gradient over aperture **2604** changes and the direction of the radiated beam in the far field also changes. For example, with the first and second periodic arrangements of sub-wavelength capacitive patches in a first position with respect to each other, a first radiated beam **2614** is generated by aperture **2604** by reflection in response to receipt of incident wave **2613**. Moving top dielectric layer **2608** with the first periodic arrangement of sub-wavelength capacitive patches formed thereon in a first direction **2600** without moving bottom dielectric layer **2612** or the bottom metal layer, a second radiated beam **2616** is generated by aperture **2604** by reflection in response to receipt of incident wave **2613**. Moving top dielectric layer **2608** with the first periodic arrangement of sub-wavelength capacitive patches formed thereon further in the first direction **2600** without moving bottom dielectric layer **2612** or the bottom metal layer, a third radiated beam **2618** is generated by aperture **2604** by reflection in response to receipt of incident wave **2613**. As a result, relative lateral movement between top dielectric layer **2608** with the first periodic arrangement of sub-wavelength capacitive patches and bottom dielectric layer **2612** with the second periodic arrangement of sub-wavelength capacitive patches steers a radiated beam.

Illumination of aperture **2604** by incident wave **2613** creates an electric field distribution over aperture **2604**. Referring to FIG. **27***a*, a magnitude **2700** of the electric field distribution over aperture **2604** is shown. The phase of the electric field distribution over the antenna aperture determines its radiation properties in the far field. Referring to FIG. **27***b*, a first phase distribution **2702** of the electric field distribution over aperture **2604** is shown that results in radiation of first radiated beam **2614**. A second phase distribution **2704** of the electric field distribution over aperture **2604** is shown that results in radiation of second radiated beam **2616**. A third phase distribution **2706** of the electric field distribution over aperture **2604** is shown that results in radiation of third radiated beam **2618**. In particular, the phase shift gradient of the E-field distribution over aperture **2604** determines the direction of the maximum radiation of transmitter **2602** in the far-field. Either or both periodic structure can be moved with respect to the other to achieve the beam steering.

As another example, referring to FIG. **28**, a rotational movement is shown between layers of a multi-layer periodic structure. Referring to FIG. **28**, a perspective view of a transmitter **2802** is shown. Transmitter **2802** may include feed antenna **602** (not shown) and an aperture **2804**. Aperture **2804** is populated by pixels **2806** acting as spatial phase shifters. These phase shifters are the unit cells of an anisotropic impedance surface whose impedance is a function of the polarization of the incident wave. In such a structure, if the polarization of the incident wave is rotated, the phase shift gradient provided over aperture **2804** of transmitter **2802** can be changed dynamically. Thus, the direction of the radiated field in the far field can be changed as well. There is no need to physically rotate aperture **2804**. Feed antenna **602** can be rotated or the direction of polarization of feed antenna **602** can be electronically tuned. However, this will change the polarization of the radiated field as well, which may not be desirable in certain applications.

Equivalently the polarization of incident wave **606** can be set and aperture **2804** rotated in its plane to change the direction of the radiated field in the far field and accomplish beam steering. The polarization of the radiated wave is maintained, but the direction of maximum radiation can still change.

A first relative rotation may generate a first radiated beam **2808** from aperture **2804** by reflection in response to receipt of incident wave **2613**. A second relative rotation may generate a second radiated beam **2810** from aperture **2804** by reflection in response to receipt of incident wave **2613**. A third relative rotation may generate a third radiated beam **2812** from aperture **2804** by reflection in response to receipt of incident wave **2613**.

Referring to FIG. **29***a*, a magnitude **2900** of the electric field distribution over aperture **2804** is shown. Referring to FIG. **29***b*, a first phase distribution **2902** of the electric field distribution over aperture **2804** is shown that results in radiation of first radiated beam **2808**. A second phase distribution **2904** of the electric field distribution over aperture **2804** is shown that results in radiation of second radiated beam **2810**. A third phase distribution **2906** of the electric field distribution over aperture **2804** is shown that results in radiation of third radiated beam **2812**.

The word “illustrative” is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as “illustrative” is not necessarily to be construed as preferred or advantageous over other aspects or designs. Further, for the purposes of this disclosure and unless otherwise specified, “a” or “an” means “one or more”. Still further, using “and” or “or” in the detailed description is intended to include “and/or” unless specifically indicated otherwise. The illustrative embodiments may be implemented as a method, apparatus, or article of manufacture using standard programming and/or engineering techniques to produce software, firmware, hardware, or any combination thereof to control a computer to implement the disclosed embodiments.

Any directional references used herein, such as left side, right side, top, bottom, back, front, up, down, above, below, etc., are for illustration only based on the orientation in the drawings selected to describe the illustrative embodiments.

The foregoing description of illustrative embodiments of the disclosed subject matter has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the disclosed subject matter to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed subject matter. The embodiments were chosen and described in order to explain the principles of the disclosed subject matter and as practical applications of the disclosed subject matter to enable one skilled in the art to utilize the disclosed subject matter in various embodiments and with various modifications as suited to the particular use contemplated.

What is claimed is:

1. A tunable phase shifter comprising:
- a spatial phase shift element comprising
  - a dielectric substrate; and
  - a conductive antenna element mounted on the dielectric substrate;
- a conducting sheet mounted a distance from the spatial phase shift element and configured to reflect an electromagnetic wave through the spatial phase shift element; and
- an actuator mounted to the conducting sheet and configured to move the conducting sheet relative to the spatial phase shift element to change the distance between the conducting sheet and the spatial phase shift element,
- wherein the conductive antenna element is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave, wherein the distance between the conducting sheet and the spatial phase shift element can be changed to adjust a phase shift of the reflected electromagnetic wave.

2. The tunable phase shifter of claim **1**, wherein the conductive antenna element is selected from the group consisting of a patch antenna element, a resonant dipole antenna element, a tri-pole antenna element, a Jerusalem cross antenna element, a split ring resonator antenna element, a multi-element dipole antenna element, and a leaky wave antenna element.

3. The tunable phase shifter of claim **1**, wherein the conducting sheet is formed of a flexible membrane coated with a conductor.

4. The tunable phase shifter of claim **3**, wherein the flexible membrane is moved relative to an anchor point of the flexible membrane to change the distance between the conducting sheet and the spatial phase shift element.

5. The tunable phase shifter of claim **4**, wherein the flexible membrane is anchored at a plurality of points.

6. The tunable phase shifter of claim **1**, wherein the conducting sheet is tilted relative to the spatial phase shift element to change the distance between the conducting sheet and the spatial phase shift element.

7. The tunable phase shifter of claim **1**, further comprising a spacer positioned between the conducting sheet and the spatial phase shift element, wherein the spacer is filled with a dielectric material.

8. The tunable phase shifter of claim **7**, wherein the dielectric material is air.

9. A phased array antenna comprising:
- a feed antenna configured to radiate an electromagnetic wave;
- a plurality of spatial phase shift elements distributed linearly in a direction, wherein each spatial phase shift element of the plurality of spatial phase shift elements comprises
  - a dielectric substrate; and
  - a conductive antenna element mounted on the dielectric substrate; and
- a conducting sheet mounted a distance from the plurality of spatial phase shift elements and configured to reflect the radiated electromagnetic wave through the plurality of spatial phase shift elements;
- wherein the conductive antenna element of each of the plurality of spatial phase shift elements is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave, wherein the distance between the conducting sheet and the plurality of spatial phase shift elements can be changed to adjust a phase shift of the reflected electromagnetic wave.

10. The phased array antenna of claim **9**, wherein the plurality of spatial phase shift elements are distributed linearly in two directions to form a two-dimensional array.

11. The phased array antenna of claim **9**, further comprising an actuator mounted to the conducting sheet and configured to tilt the conducting sheet relative to the plurality of spatial phase shift elements to change the distance between the conducting sheet and the plurality of spatial phase shift elements.

12. The phased array antenna of claim **9**, wherein the conducting sheet comprises a plurality of sections, wherein the plurality of sections are independently moveable.

13. The phased array antenna of claim **12**, further comprising an actuator mounted to each of the plurality of sections, wherein the actuator is configured to move the section to which it is mounted to change the distance between the section and the plurality of spatial phase shift elements.

14. The phased array antenna of claim **12**, wherein a number of the plurality of sections is equal to a number of the plurality of spatial phase shift elements.

15. The phased array antenna of claim **12**, wherein a number of the plurality of sections is less than a number of the plurality of spatial phase shift elements.

16. The tunable phase shifter of claim **9**, wherein the feed antenna is selected from the group consisting of a patch antenna, a dipole antenna, a monopole antenna, a helical antenna, a microstrip antenna, a fractal antenna, a feed horn, a slot antenna, an end fire antenna, and a parabolic antenna.

17. The phased array antenna of claim **9**, wherein the feed antenna is mounted between the plurality of spatial phase shift elements and the conducting sheet.

18. The phased array antenna of claim **9**, further comprising a spacer positioned between the conducting sheet and the plurality of spatial phase shift elements, wherein the spacer is filled with a dielectric material.

19. A phased array antenna system comprising:
- a feed antenna configured to radiate an electromagnetic wave;
- a radiating antenna comprising
  - a plurality of spatial phase shift elements distributed linearly in a direction, wherein each spatial phase shift element of the plurality of spatial phase shift elements comprises
    - a dielectric substrate; and
    - a conductive antenna element mounted on the dielectric substrate; and
  - a conducting sheet mounted a distance from the plurality of spatial phase shift elements and configured to reflect the radiated electromagnetic wave through the plurality of spatial phase shift elements, wherein the conductive antenna element of each of the plurality of spatial phase shift elements is configured to radiate a second electromagnetic wave in response to receipt of the reflected electromagnetic wave; and
- an actuator mounted to the radiating antenna and configured to change the distance between the conducting sheet and the plurality of spatial phase shift elements.

20. The phased array antenna system of claim **19**, further comprising a spacer positioned between the conducting sheet and the plurality of spatial phase shift elements, wherein the spacer is filled with a dielectric material.

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