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Abadi et al.

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(45) **Date of Patent: Aug. 30, 2016**

(54) **ELECTRICALLY-SMALL, LOW-PROFILE, ULTRA-WIDEBAND ANTENNA**

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(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 345 days.

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(65) **Prior Publication Data**

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(51) **Int. Cl.**

H01Q 9/04	(2006.01)
H01Q 1/48	(2006.01)
H01Q 5/25	(2015.01)
H01Q 5/364	(2015.01)
H01Q 9/36	(2006.01)

(52) **U.S. Cl.**
CPC ***H01Q 9/0421*** (2013.01); ***H01Q 1/48*** (2013.01); ***H01Q 5/25*** (2015.01); ***H01Q 5/364*** (2015.01); ***H01Q 9/045*** (2013.01); ***H01Q 9/0442*** (2013.01); ***H01Q 9/36*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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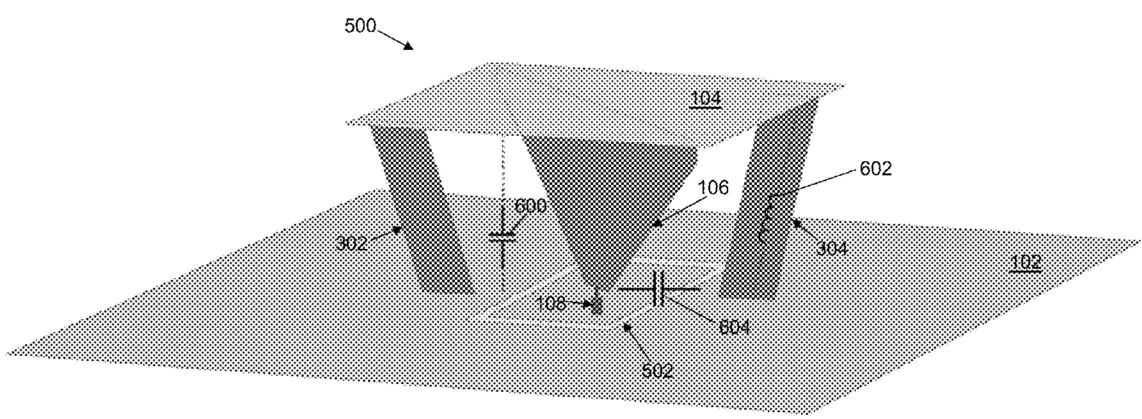
(74) *Attorney, Agent, or Firm* — Bell & Manning, LLC

(57) **ABSTRACT**

An ultra-wideband, low profile antenna is provided. The antenna includes a ground plane substrate, a feed conductor, a top hat conductor, a shorting arm, and a ring slot. The feed conductor includes a first end and a second end. The first end is configured for electrical coupling to a feed network through a feed element extending from the ground plane substrate. The top hat conductor includes a generally planar sheet mounted to the second end of the feed conductor in a first plane approximately parallel to a second plane defined by the ground plane substrate. The shorting arm includes a third end and a fourth end. The third end is mounted to the top hat conductor, and the fourth end is mounted to the ground plane substrate. The ring slot is formed in the ground plane substrate around the feed element.

20 Claims, 29 Drawing Sheets



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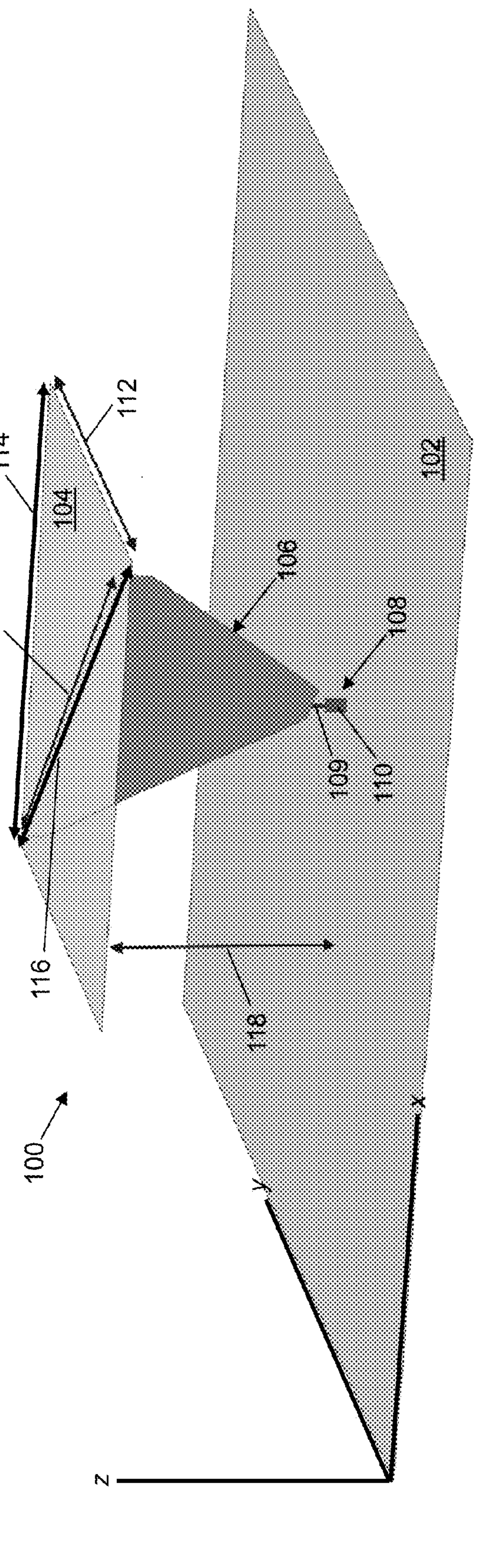


FIG. 1a

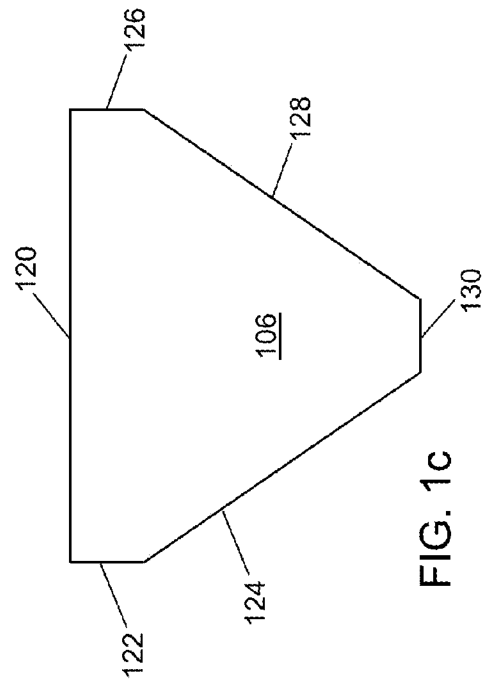


FIG. 1c

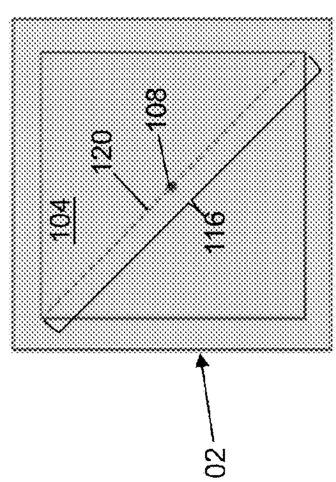


FIG. 1b

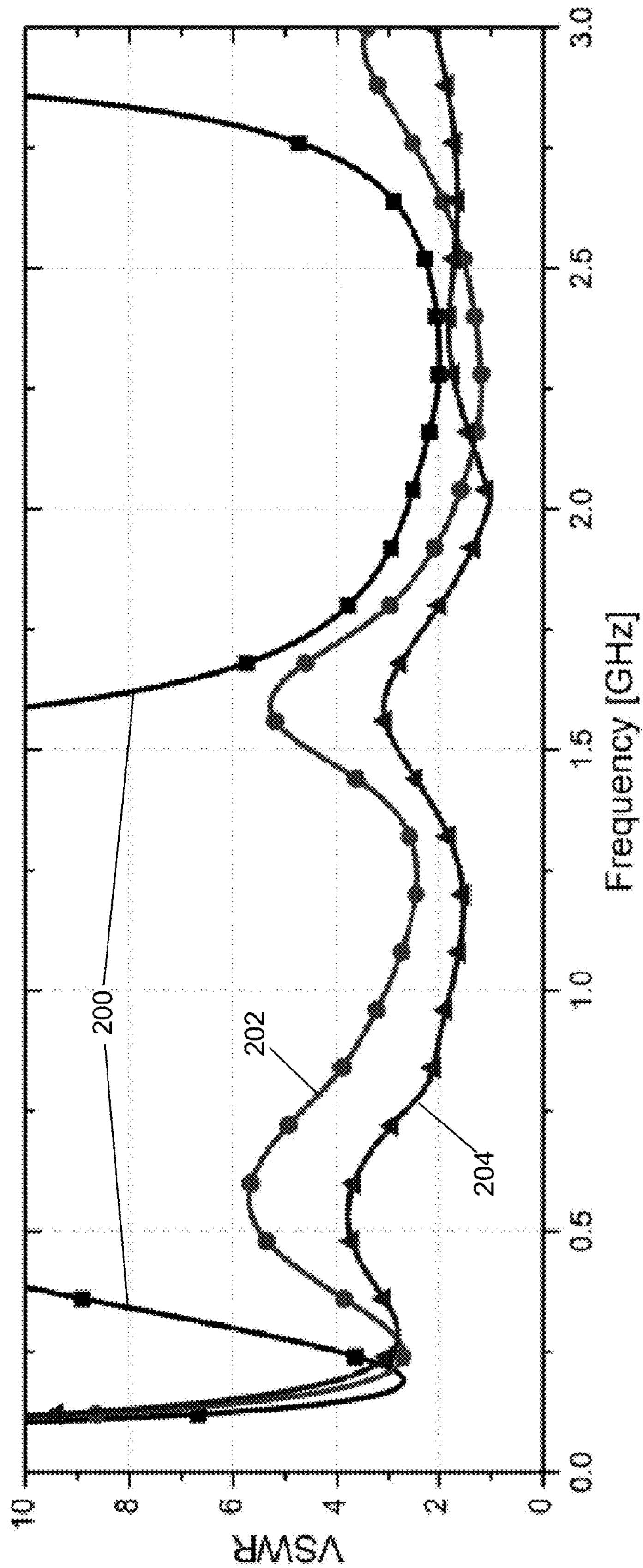


FIG. 2a

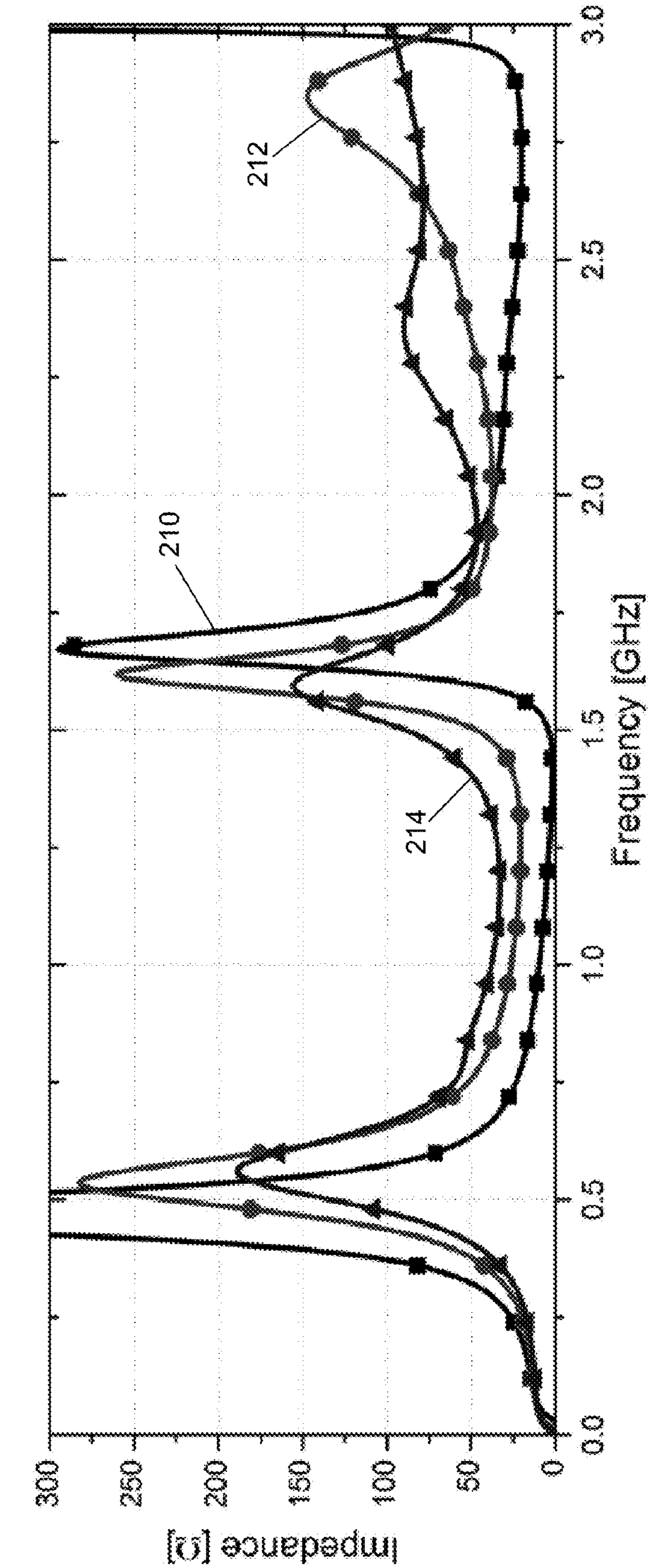

210
212
214
Frequency [GHz]
Impedance [Ω]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
50
100
150
200
250
300

FIG. 2b

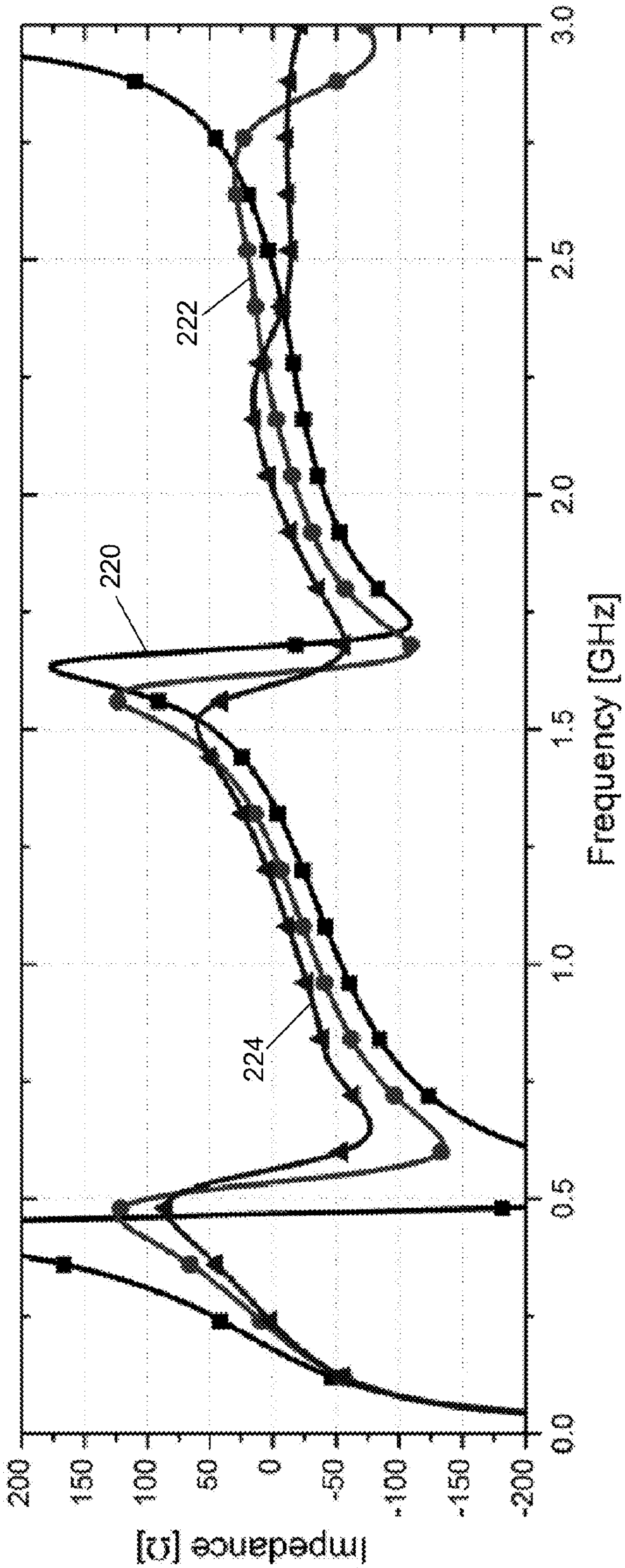

220
222
224
Frequency [GHz]
Impedance [Ω]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
200
150
100
50
0
-50
-100
-150
-200

FIG. 2c

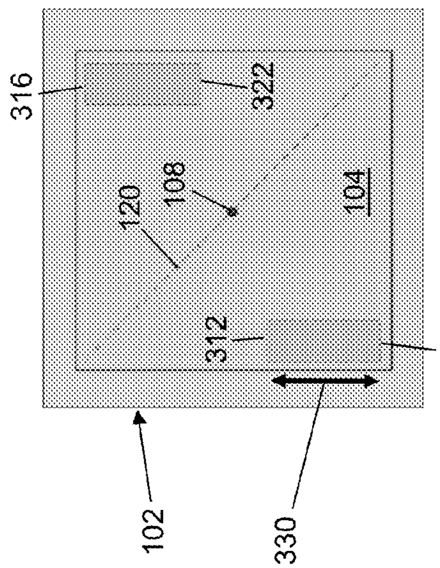

316
322
120
108
104
312
306
102
330

FIG. 3b

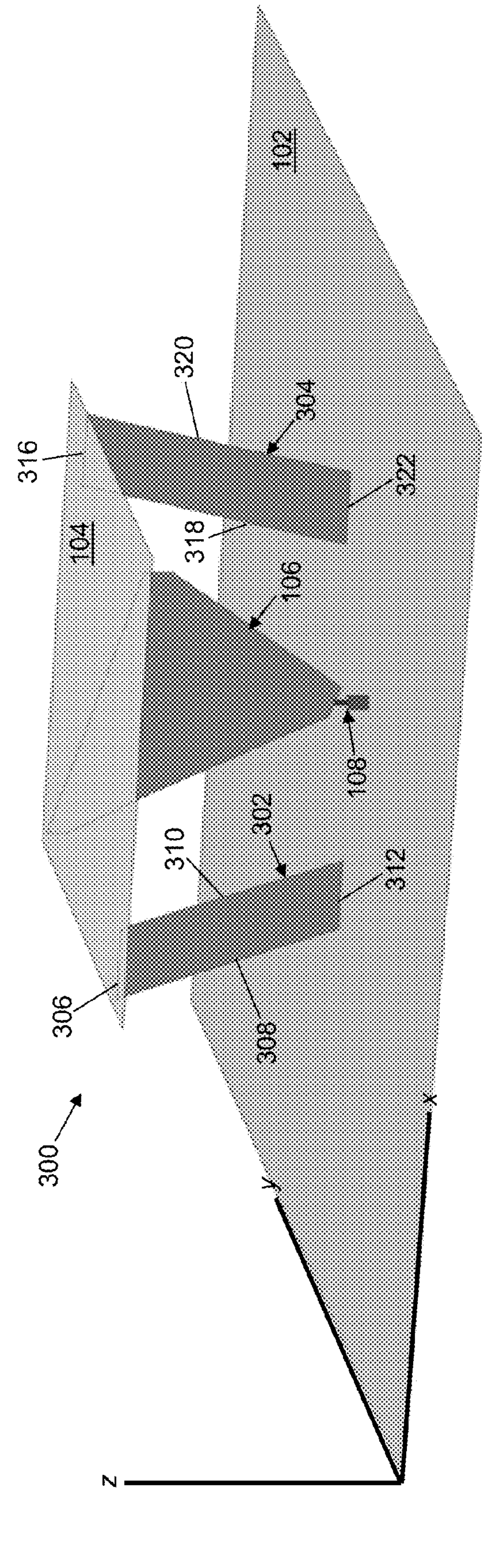

102
320
304
316
322
318
104
106
108
310
302
312
306
308
300
x
y
z

FIG. 3a

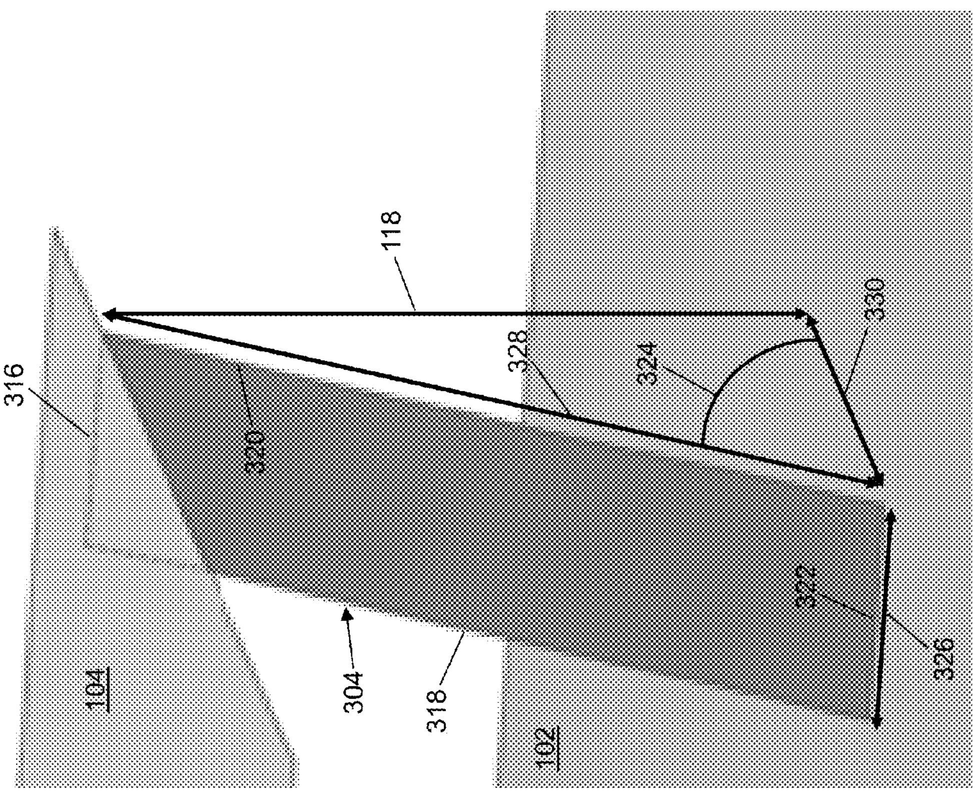


FIG. 3c

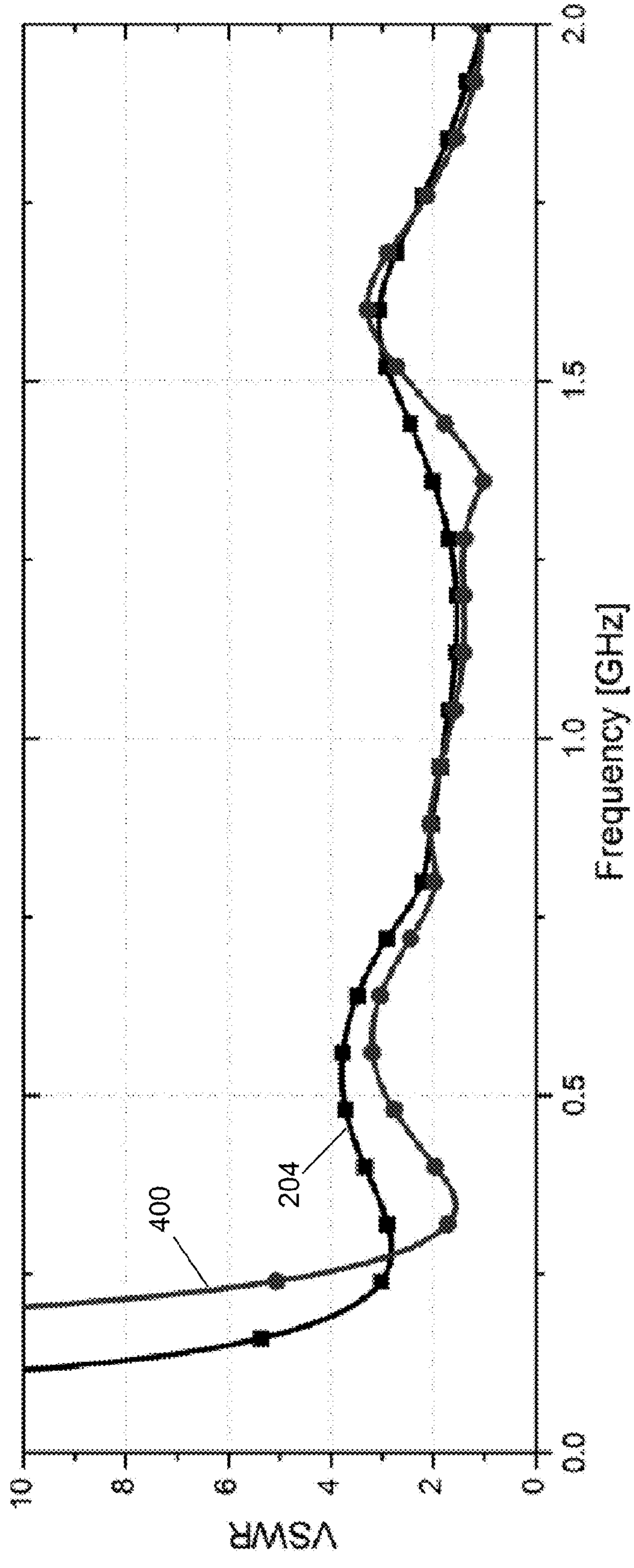


FIG. 4a

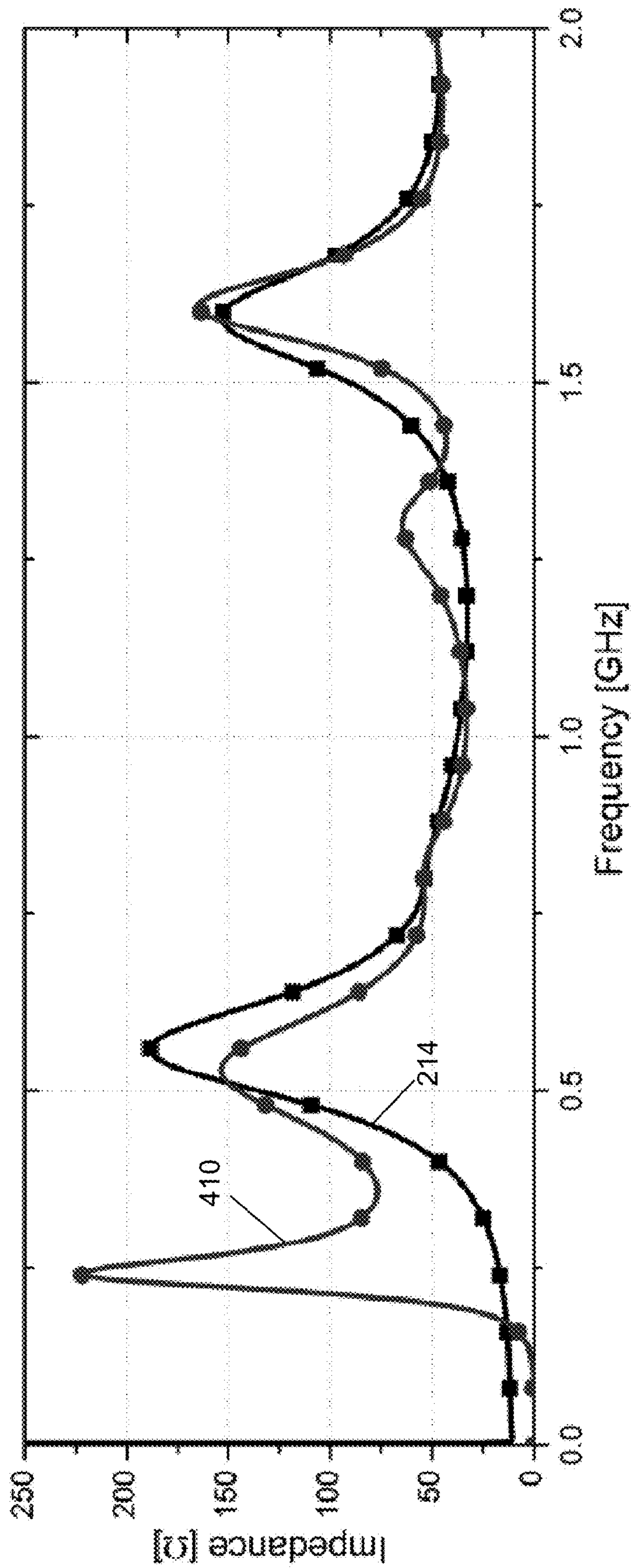
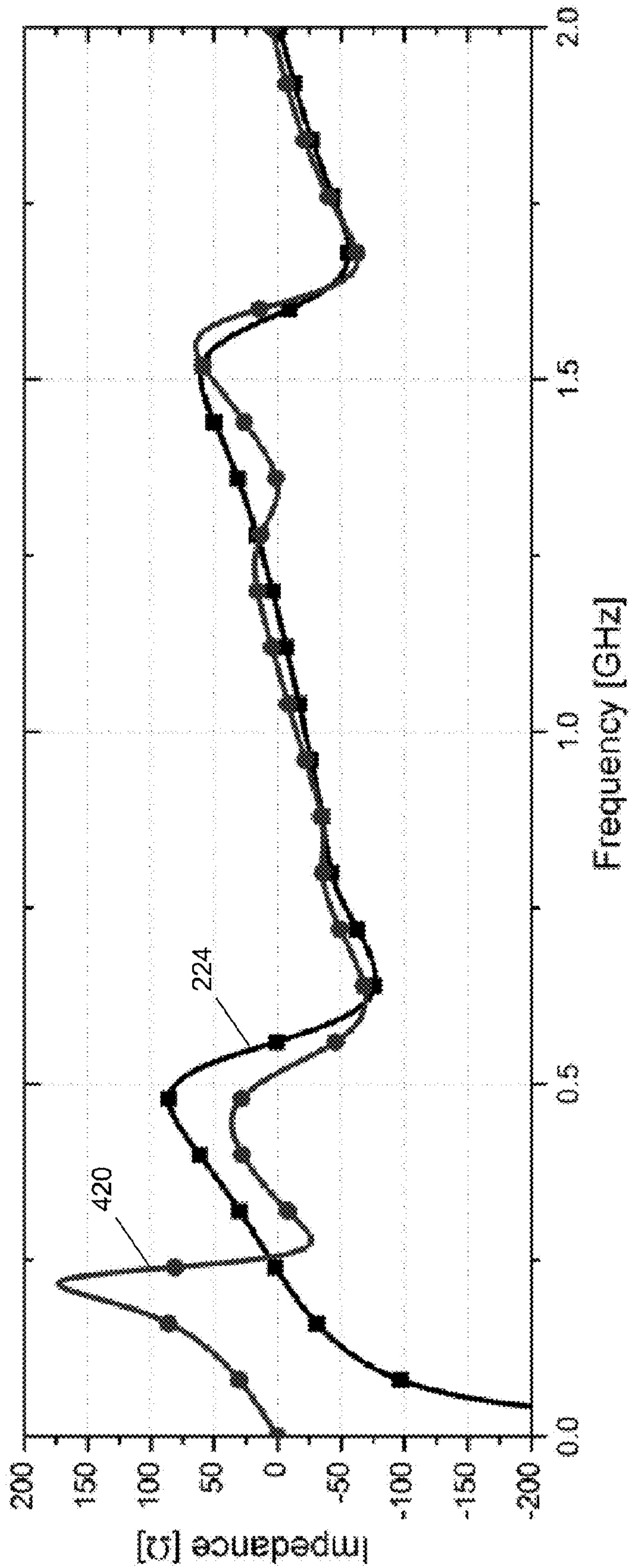

Impedance [Ω]
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
Frequency [GHz]
410
214

FIG. 4b



Impedance [Ω]
200
150
100
50
0
-50
-100
-150
-200
Frequency [GHz]
0.0
0.5
1.0
1.5
2.0
420
224

FIG. 4c

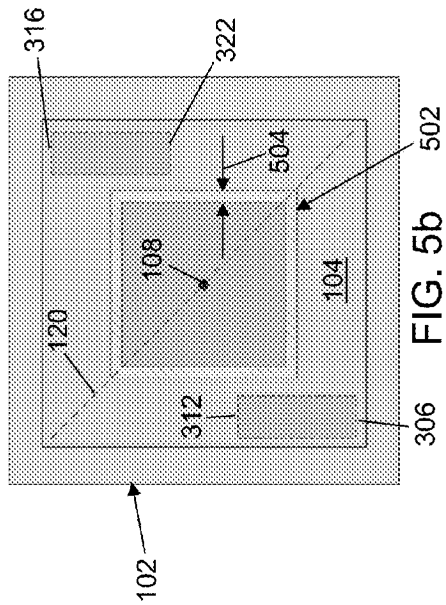

316
322
504
502
108
104
120
312
306
102

FIG. 5b

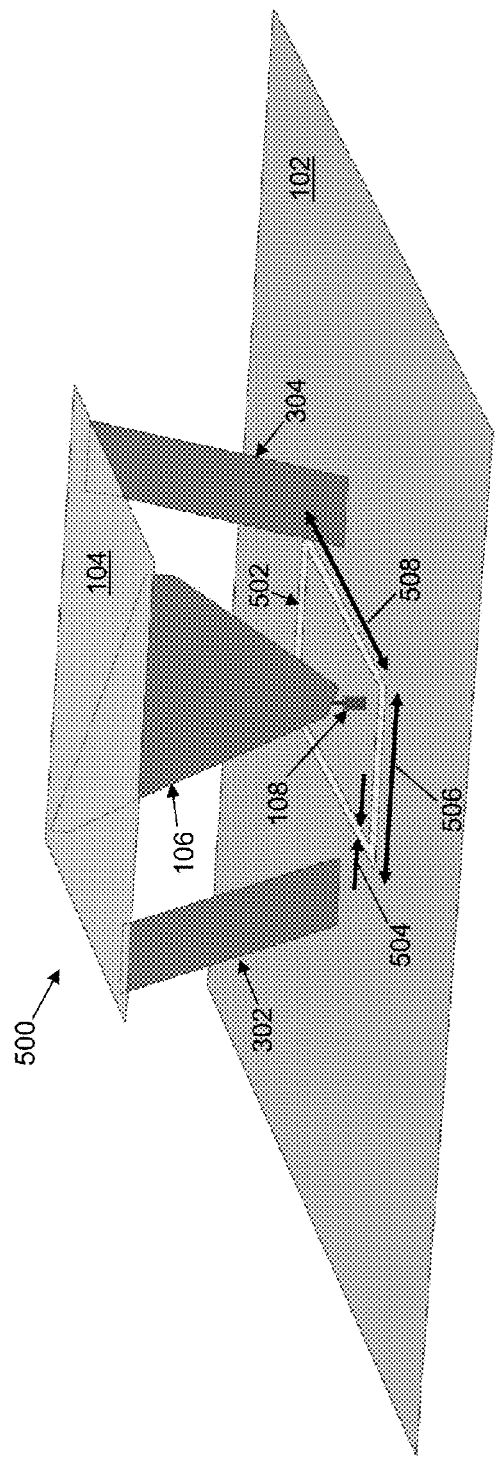

102
104
304
502
508
108
106
506
504
302
500

FIG. 5a

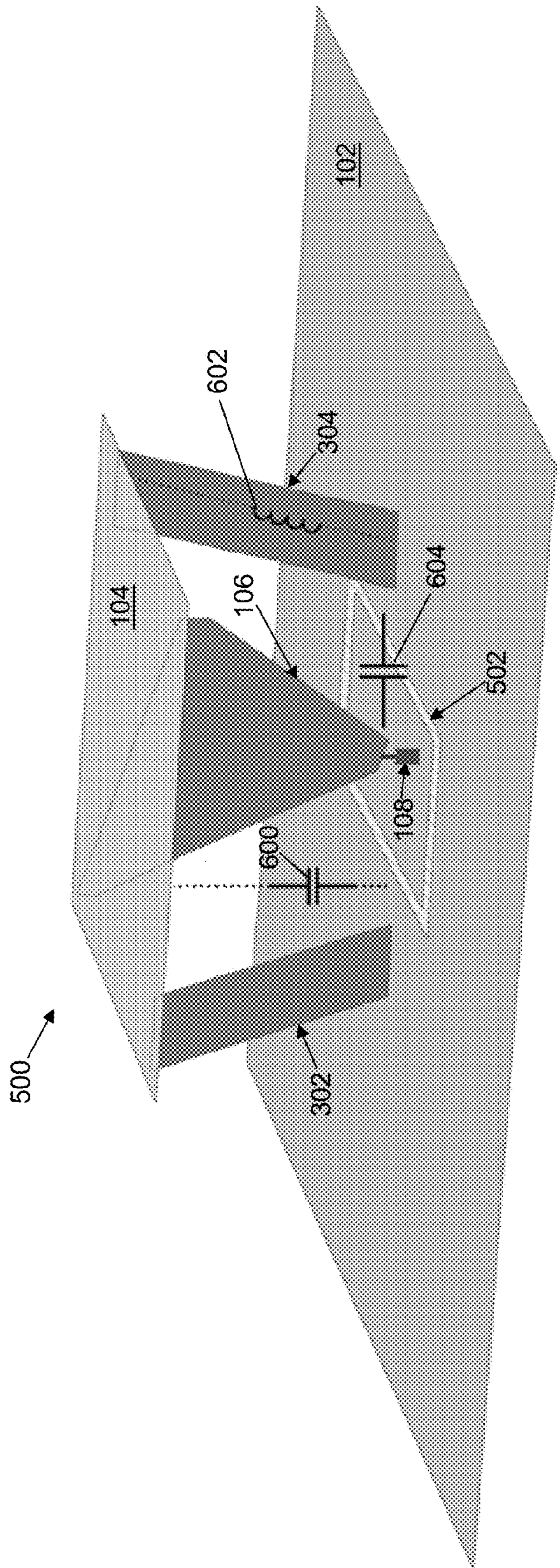


FIG. 6

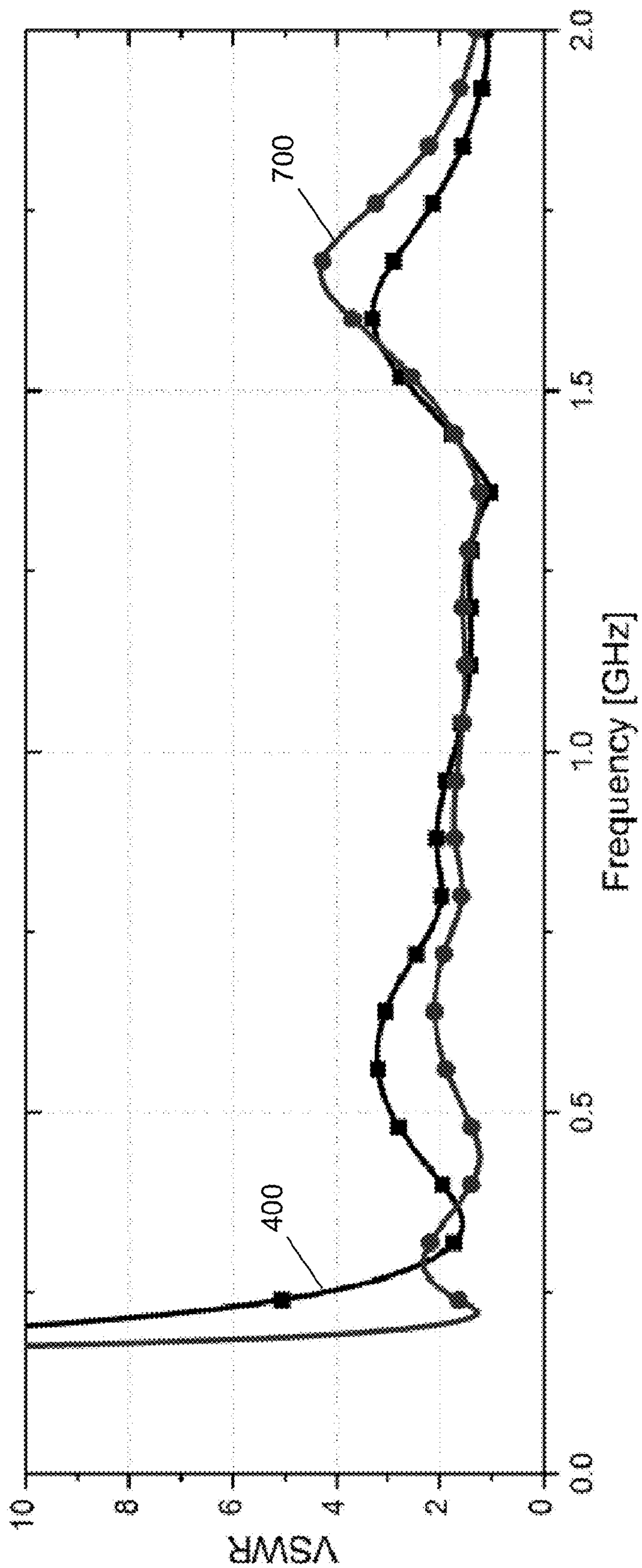
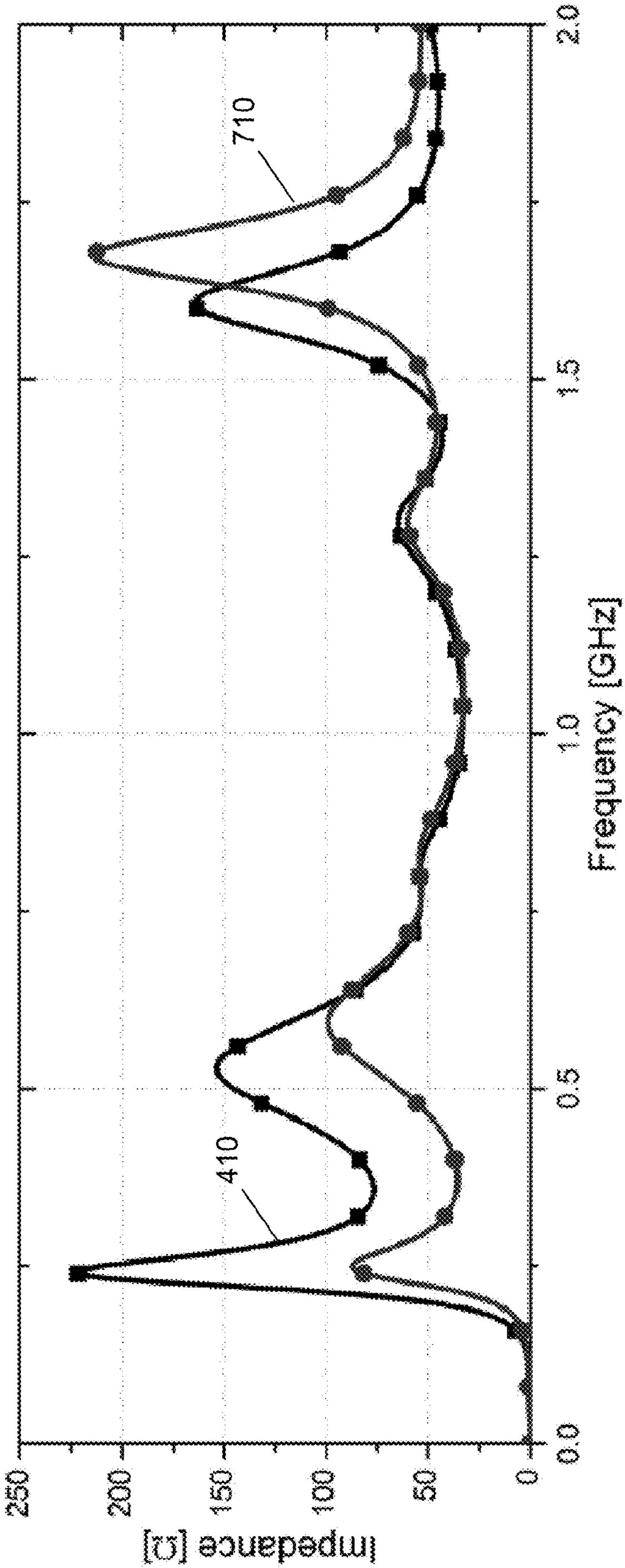


FIG. 7a



Impedance [Ω]
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
Frequency [GHz]
410
710

FIG. 7b

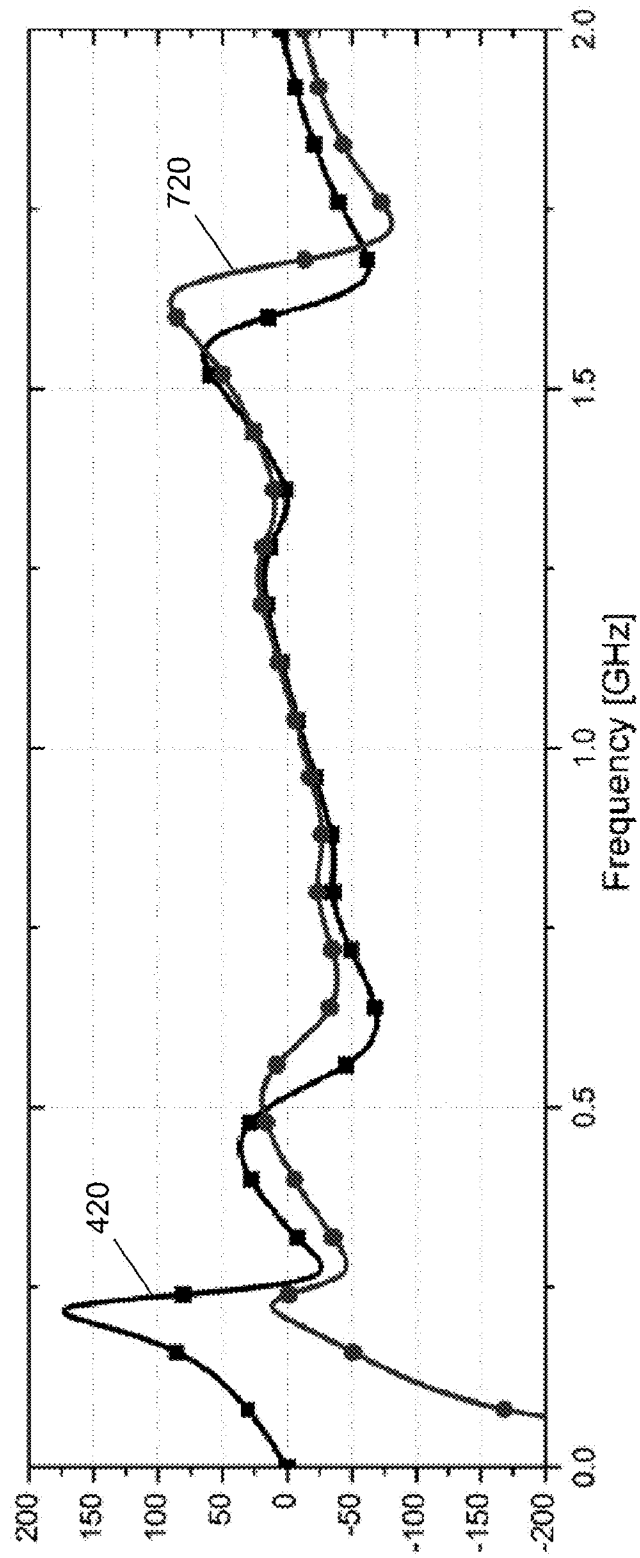

720
420
Impedance [Ω]
200
150
100
50
0
-50
-100
-150
-200
0.0
0.5
1.0
1.5
2.0
Frequency [GHz]

FIG. 7c

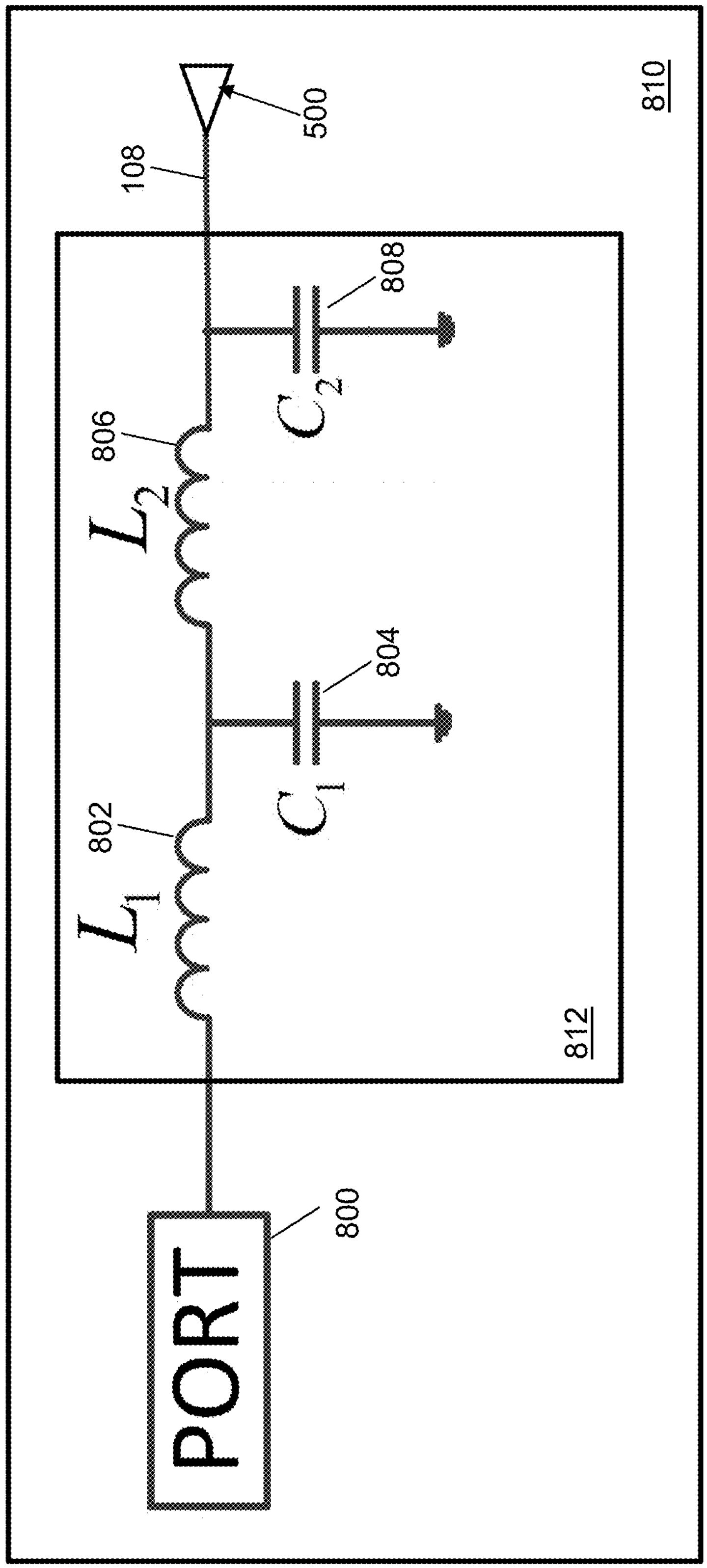


FIG. 8

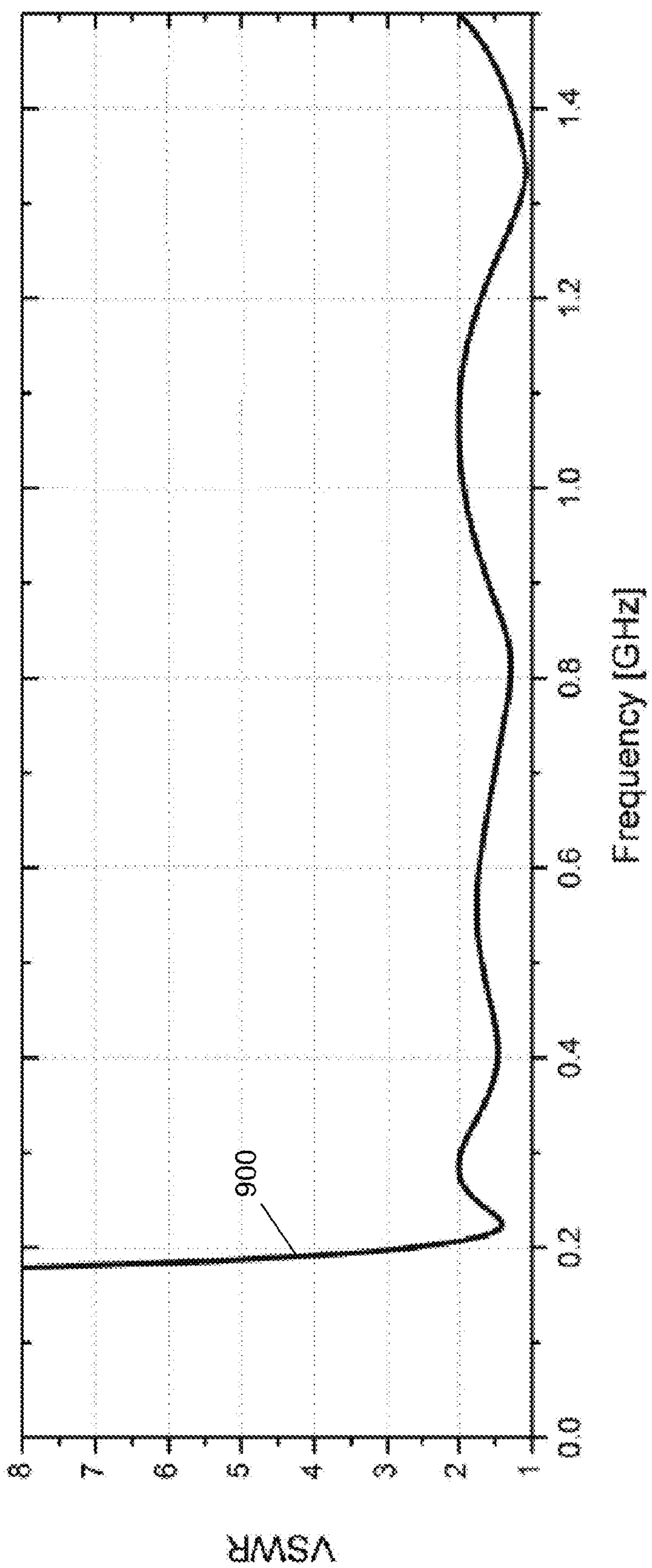
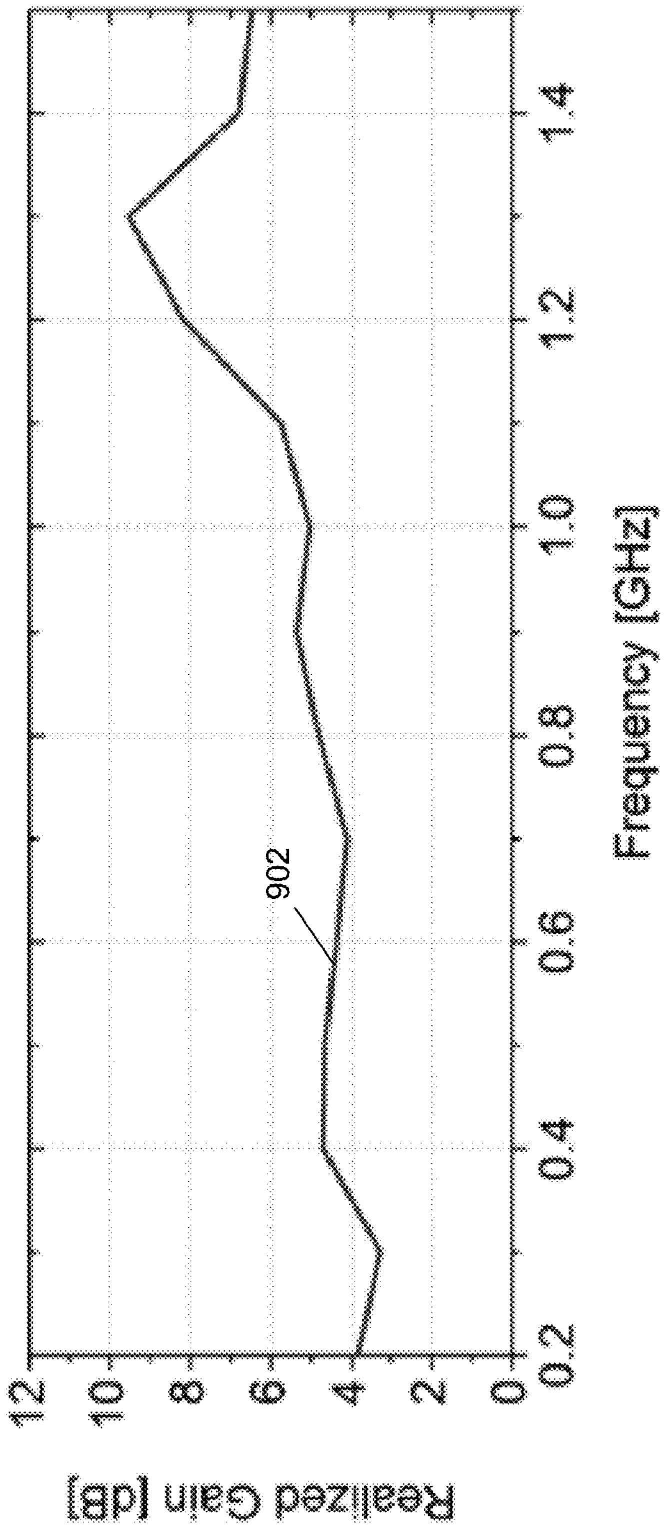


FIG. 9a



Realized Gain [dB]
0
2
4
6
8
10
12
Frequency [GHz]
0.2
0.4
0.6
0.8
1.0
1.2
1.4
902

FIG. 9b

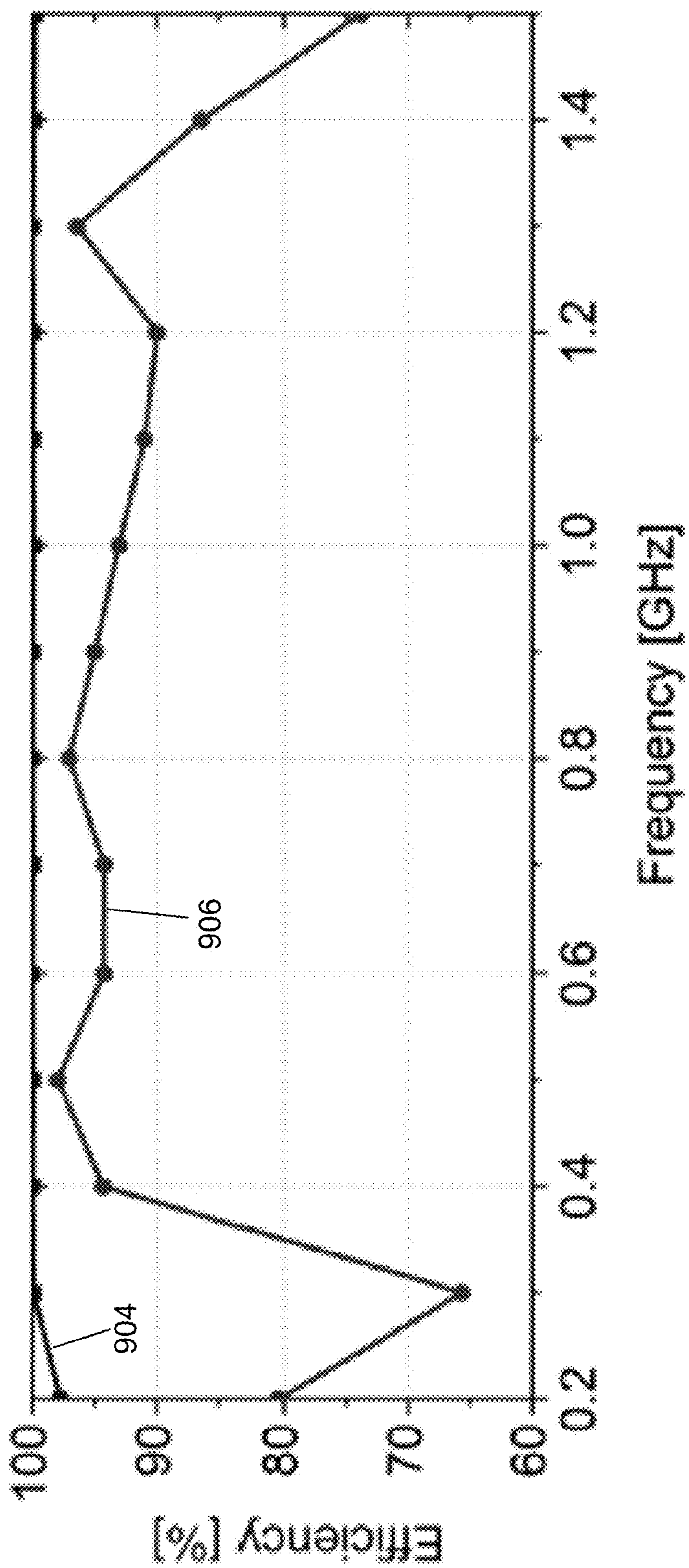

Efficiency [%]
100
90
80
70
60
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Frequency [GHz]
904
906

FIG. 9c

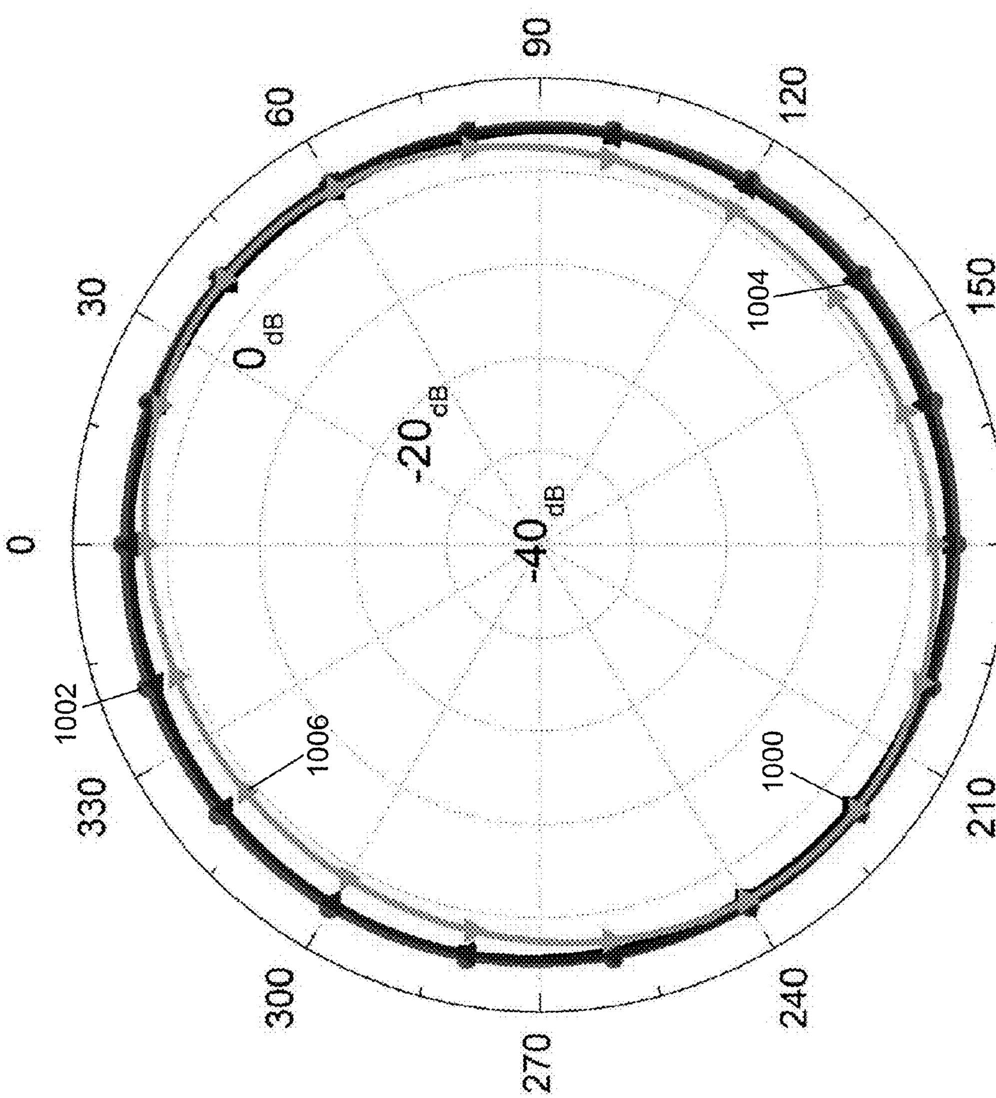

0
30
60
90
120
150
180
210
240
270
300
330
0 dB
-20 dB
-40 dB
1000
1002
1004
1006

FIG. 10a

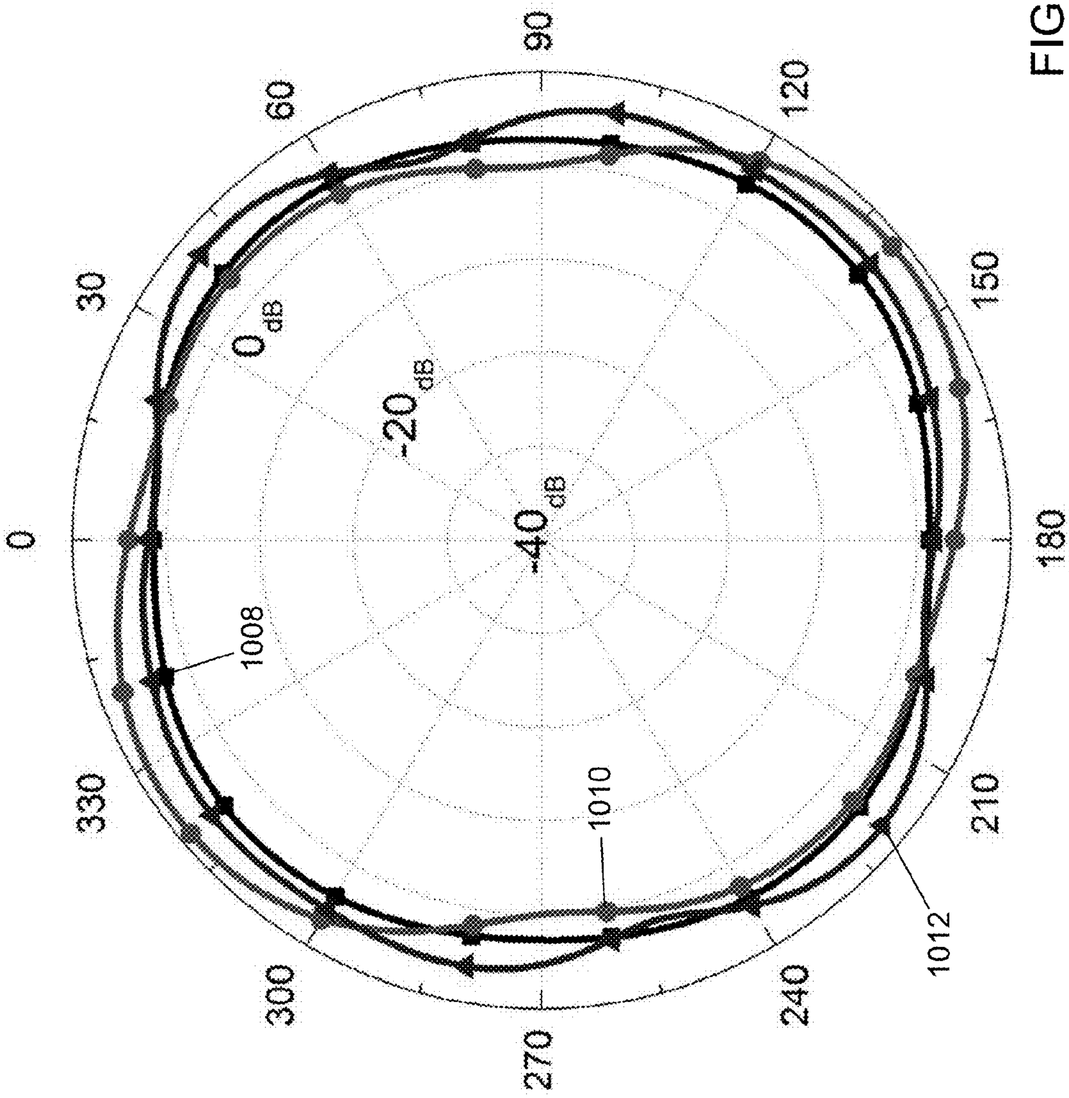

0
30
60
90
120
150
180
210
240
270
300
330
0dB
-20dB
-40dB
1008
1010
1012

FIG. 10b

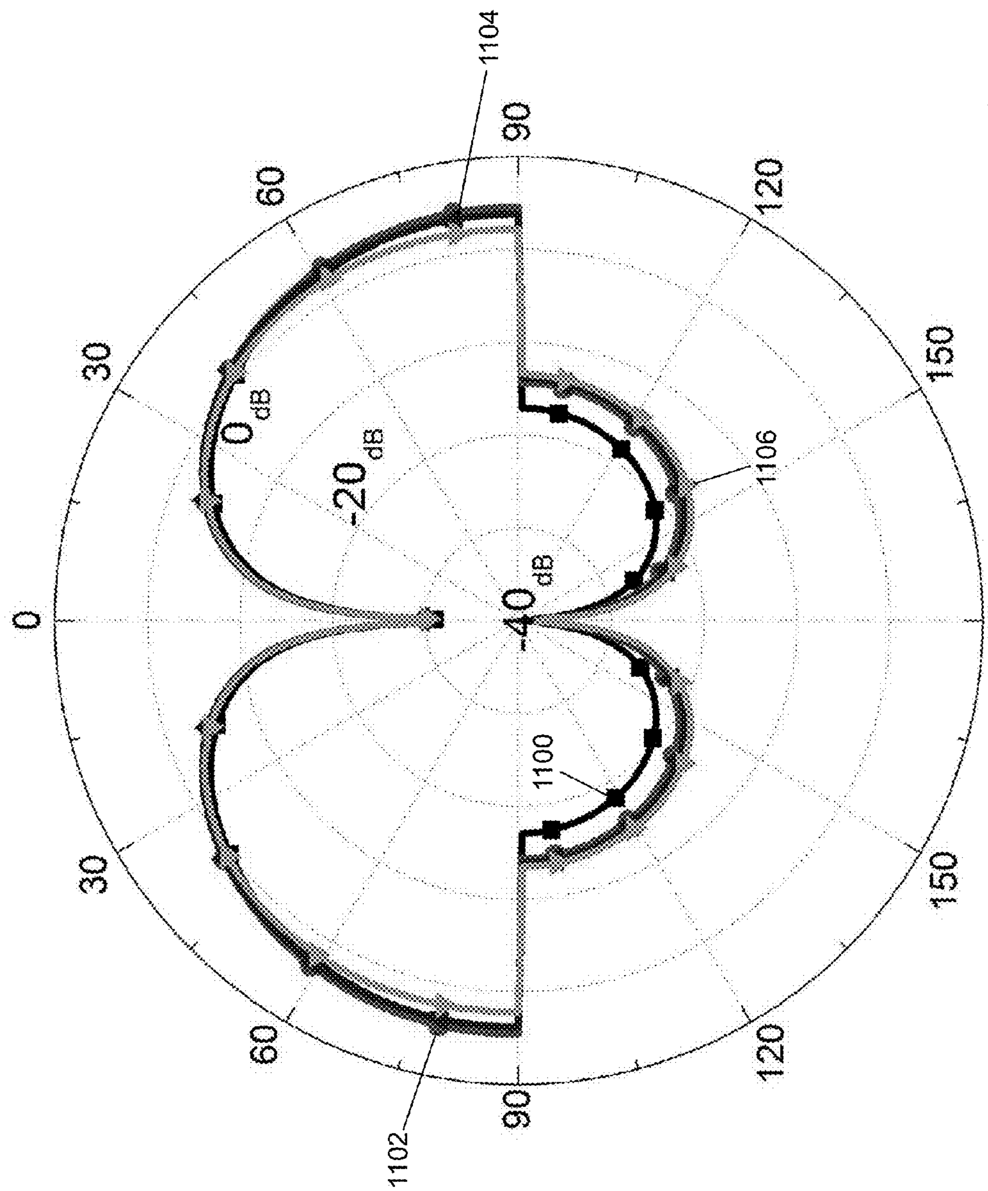

1104
1102
1106
1100
0
30
60
90
120
150
180
30
60
90
120
150
0 dB
-20 dB
-40 dB

FIG. 11a

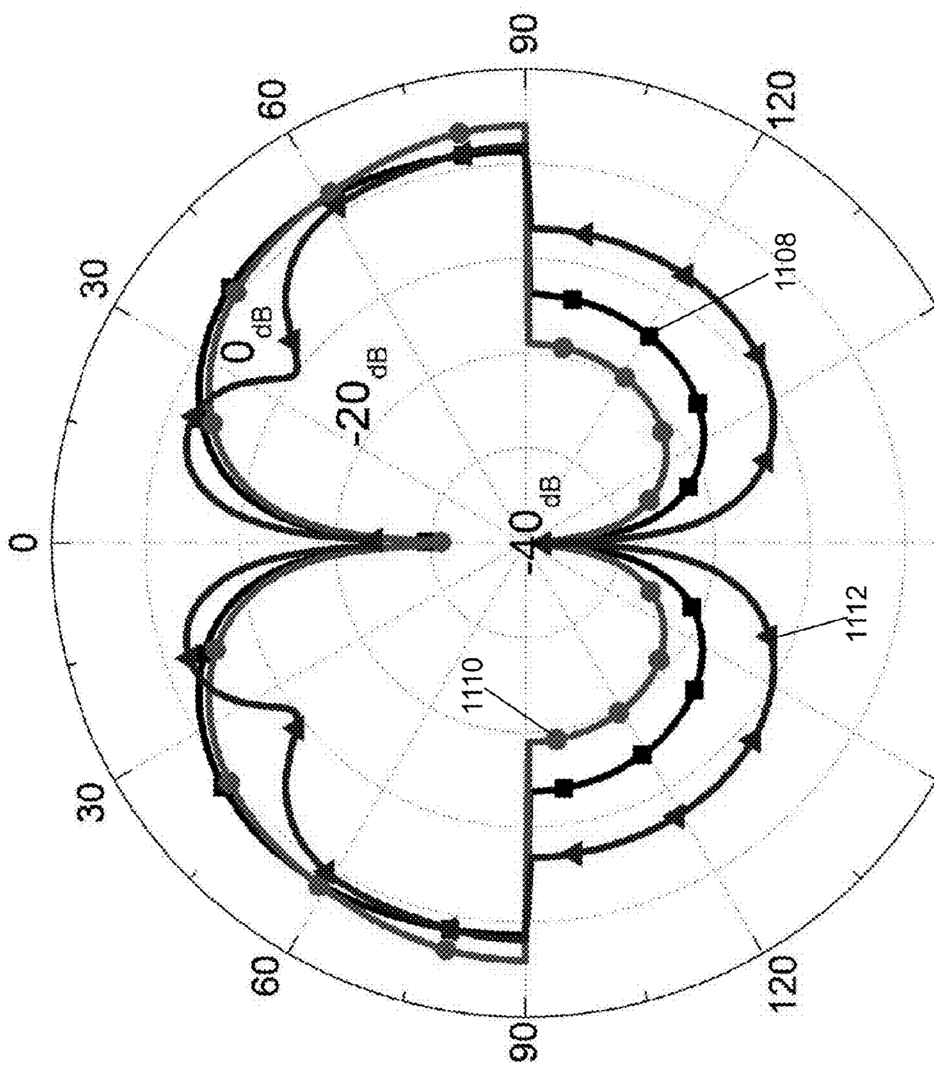

0
30
60
90
120
150
180
30
60
90
120
150
0 dB
-20 dB
-40 dB
1108
1110
1112

FIG. 11b

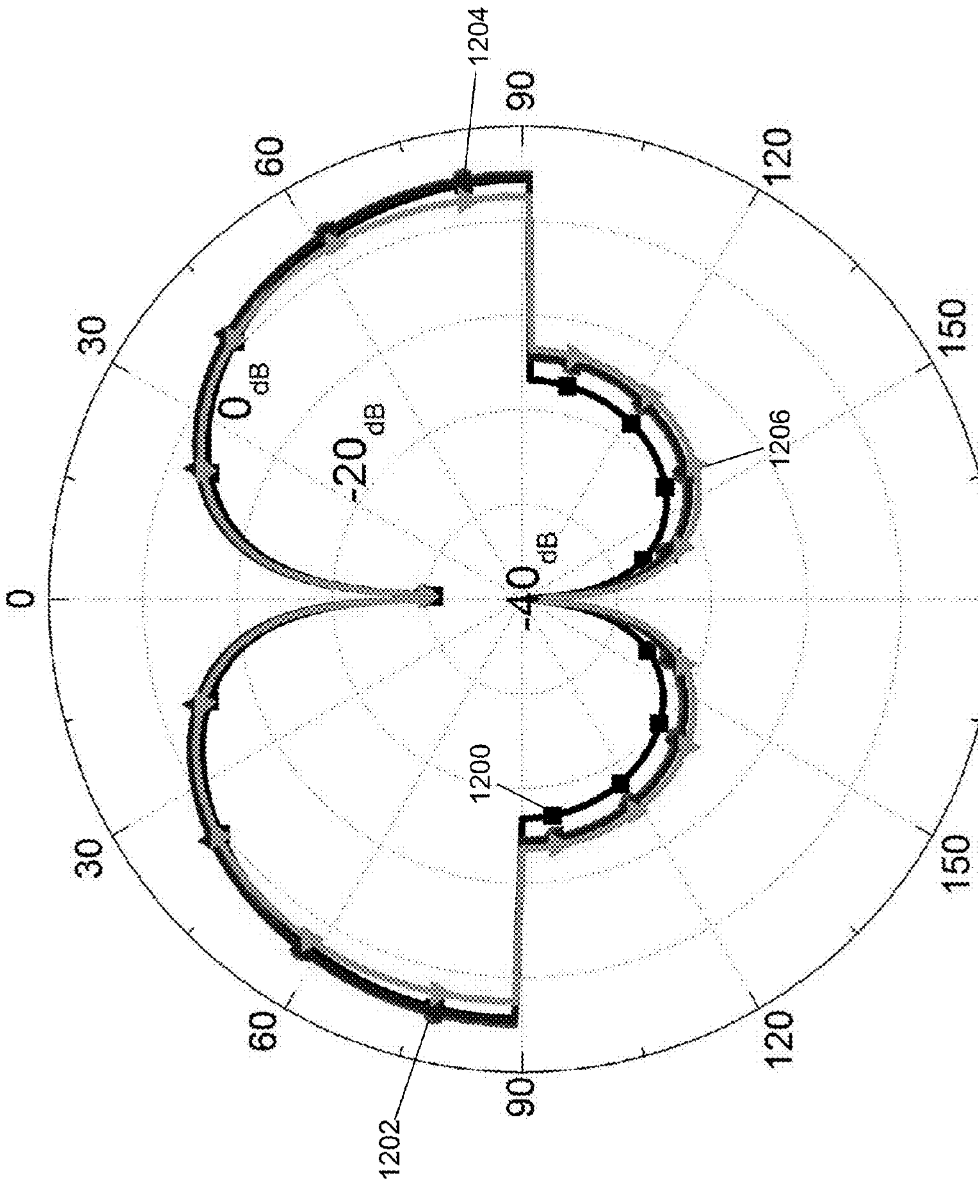

0
30
60
90
120
150
180
150
120
90
60
30
0dB
-20dB
-40dB
1200
1202
1204
1206

FIG. 12a

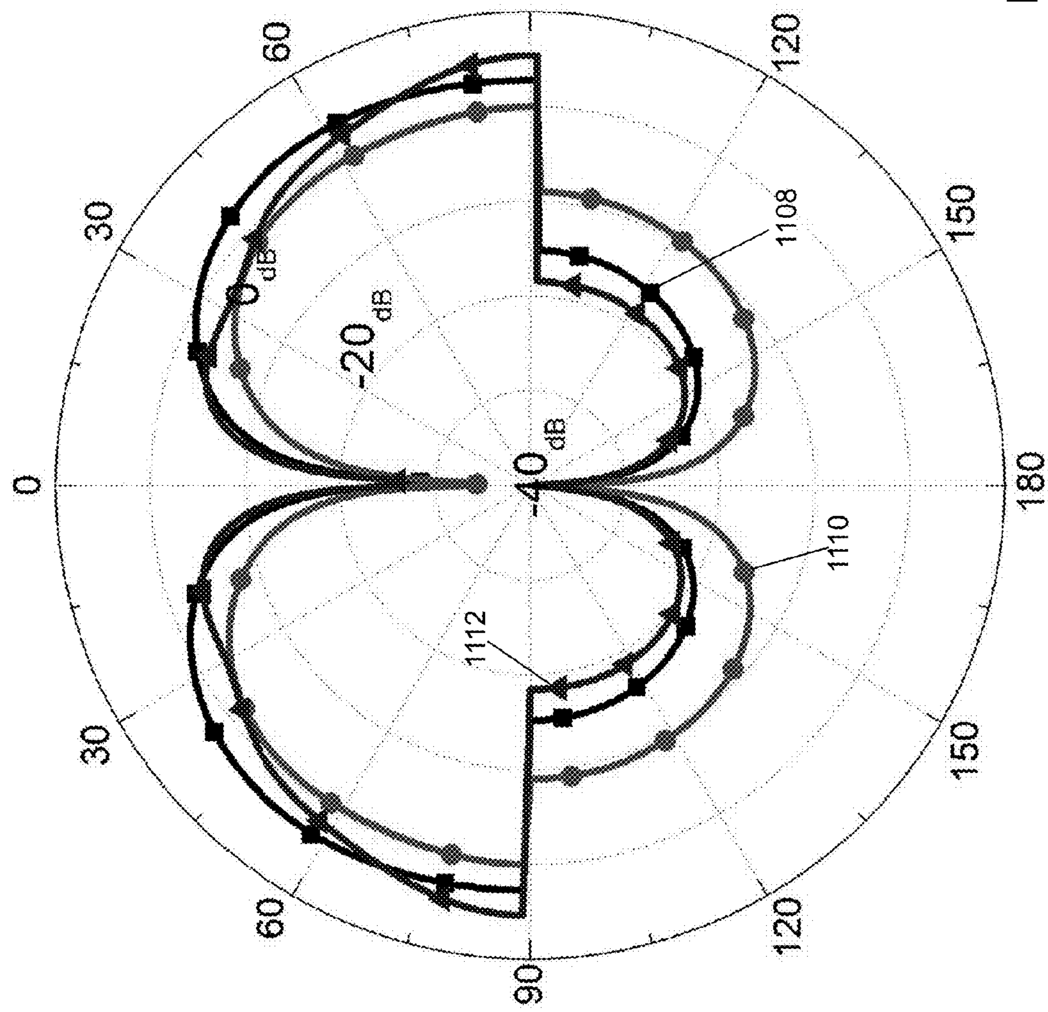


FIG. 12b

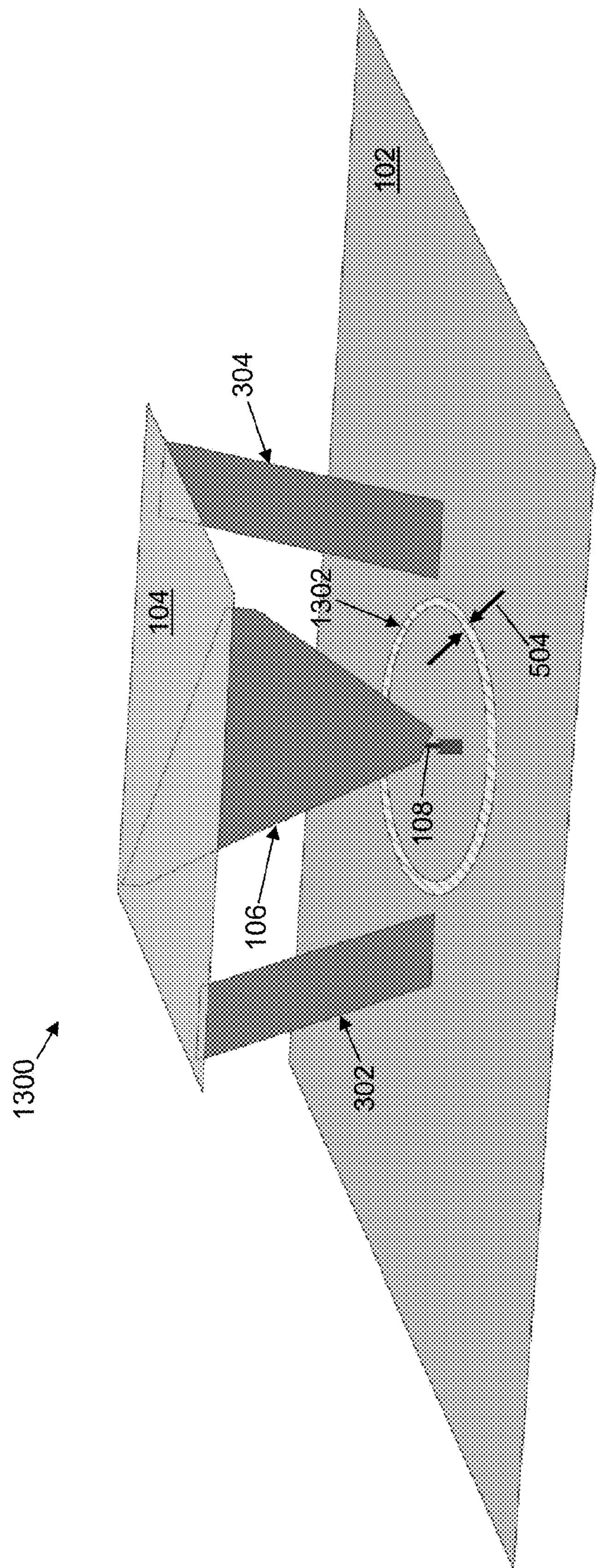


FIG. 13

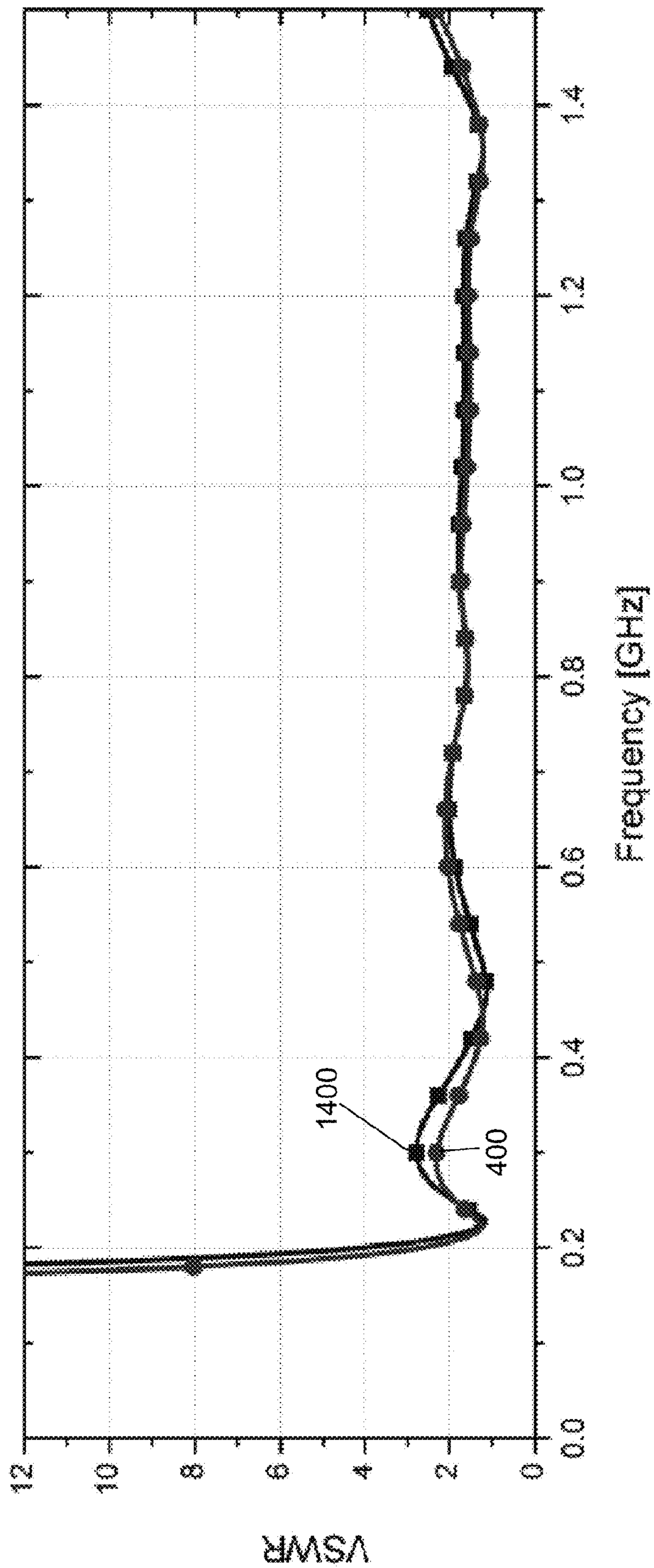


FIG. 14

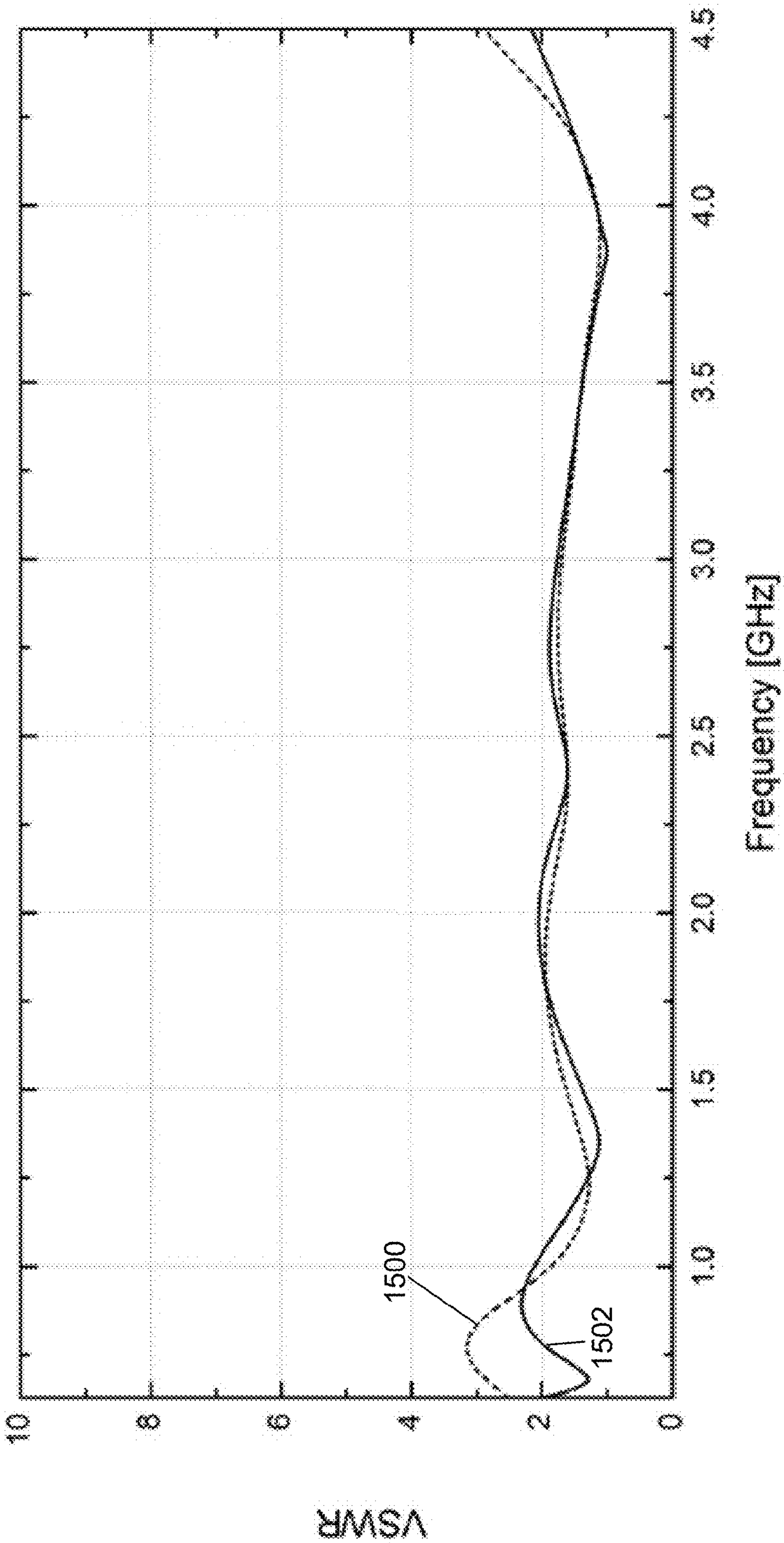
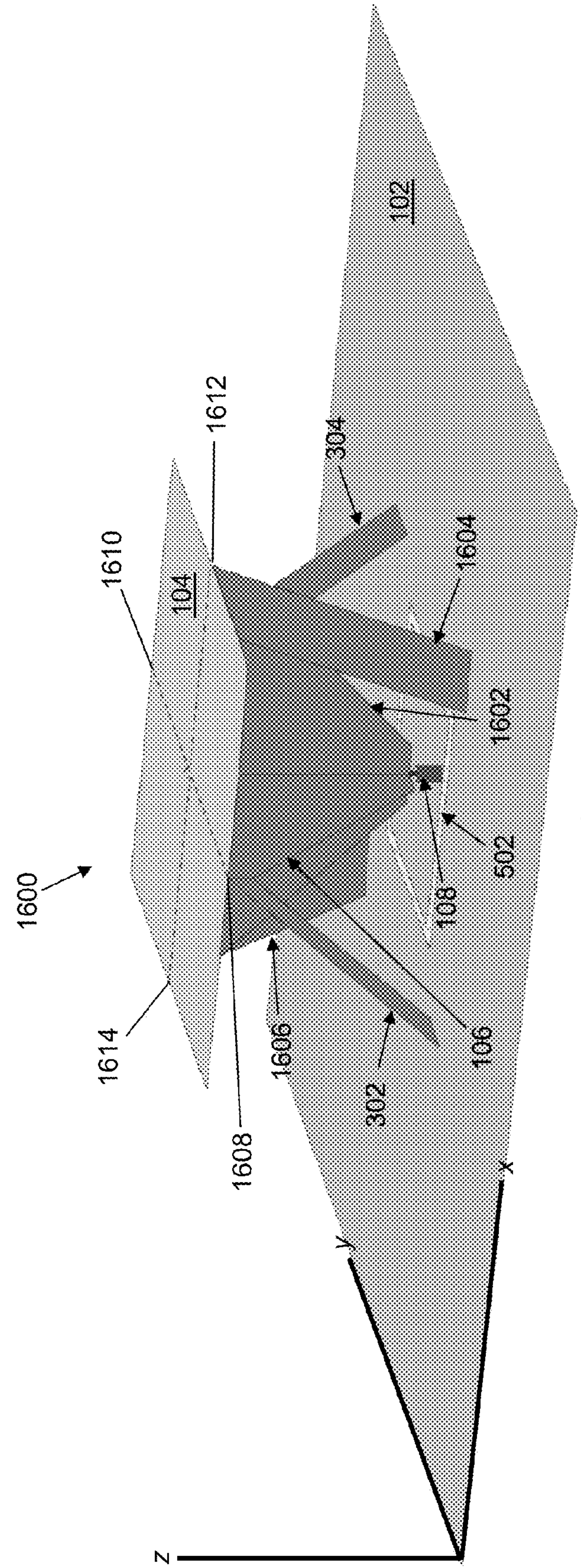


FIG. 15


1600
1610
104
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1604
1602
502
108
106
1614
1606
302
1608
x
y
z

FIG. 16a

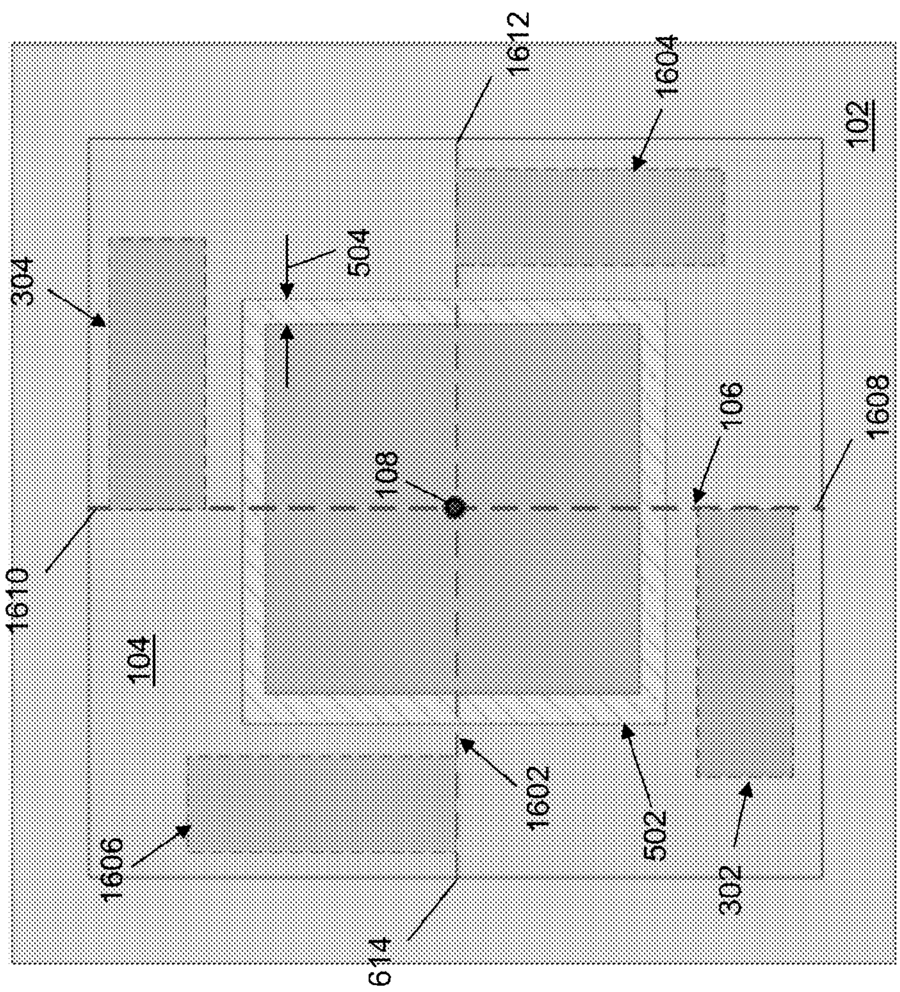
1612
1604
102
304
504
106
1608
108
1610
104
1602
502
1606
302
1614

FIG. 16b

ELECTRICALLY-SMALL, LOW-PROFILE, ULTRA-WIDEBAND ANTENNA

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under MSN141269 awarded by the Office of Naval Research and MSN139974 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

A classical monopole antenna is a type of radio antenna that consists of a straight rod-shaped conductor that is typically mounted perpendicularly over some type of conductive surface, called a ground plane. In some cases, the ground plane is the earth's surface, while in other cases, the ground plane is formed of a conductive material. The classical monopole antenna has an omnidirectional radiation pattern meaning that it radiates equal power in all azimuthal directions perpendicular to the antenna resulting in a donut shaped radiation pattern. The height of monopole antennas is inversely related to the transmission frequency because operation at low frequencies results in a very large electromagnetic wavelength. As a result, a traditional monopole antenna operating at low frequencies is also physically very large. The physically large size makes the monopole antenna challenging to use in low-profile applications at low frequencies.

SUMMARY

In an illustrative embodiment, an ultra-wideband, low profile antenna is provided. The antenna includes, but is not limited to, a ground plane substrate, a feed conductor, a top hat conductor, a shorting arm, and a ring slot. The feed conductor includes, but is not limited to, a first end and a second end. The first end is configured for electrical coupling to a feed network through a feed element extending from the ground plane substrate. The top hat conductor includes, but is not limited to, a generally planar sheet mounted to the second end of the feed conductor in a first plane approximately parallel to a second plane defined by the ground plane substrate. The shorting arm includes, but is not limited to, a third end and a fourth end. The third end is mounted to the top hat conductor, and the fourth end is mounted to the ground plane substrate. The ring slot is formed in the ground plane substrate around the feed element.

In another illustrative embodiment, a transmitter is provided. The transmitter includes, but is not limited to, a matching network circuit and an antenna. The matching network circuit is coupled to receive a signal through a port and to form a matched signal output through a feed element. The antenna includes, but is not limited to, a ground plane substrate, a feed conductor, a top hat conductor, a shorting arm, and a ring slot. The feed conductor includes, but is not limited to, a first end and a second end. The first end is configured for electrical coupling to the matching network circuit through the feed element to receive the matched signal. The top hat conductor includes, but is not limited to, a generally planar sheet mounted to the second end of the feed conductor in a first plane approximately parallel to a second plane defined by the ground plane substrate. The shorting arm includes, but is not limited to, a third end and a fourth end. The third end is mounted to the top hat conductor, and the fourth end is mounted to the ground plane substrate. The ring slot is formed in the ground plane substrate around the feed element. The matching network circuit is configured to impedance match the antenna.

Other principal features and advantages of the invention 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 invention will hereafter be described with reference to the accompanying drawings, wherein like numerals denote like elements.

FIG. **1***a* is a perspective view of a top-loaded conical antenna in accordance with an illustrative embodiment.

FIG. **1***b* is a top view of the top-loaded conical antenna of FIG. **1***a* in accordance with an illustrative embodiment.

FIG. **1***c* is a side view of a feed conductor of the top-loaded conical antenna of FIG. **1***a* in accordance with an illustrative embodiment.

FIG. **2***a* is a graph showing a voltage standing wave ratio (VSWR) determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for a top edge of a conical structure.

FIG. **2***b* is a graph showing an input resistance determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for the top edge of the conical structure.

FIG. **2***c* is a graph showing an input reactance determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for the top edge of the conical structure.

FIG. **3***a* is a perspective view of a top-loaded conical antenna including a plurality of shorting arms in accordance with an illustrative embodiment.

FIG. **3***b* is a top view of the top-loaded conical antenna of FIG. **3***a* in accordance with an illustrative embodiment.

FIG. **3***c* is a perspective view of the top-loaded conical antenna of FIG. **3***a* zoomed to show a shorting arm in accordance with an illustrative embodiment.

FIG. **4***a* is a graph showing a VSWR determined by simulating the performance of the antenna of FIGS. **1***a* and **3***a*.

FIG. **4***b* is a graph showing an input resistance determined by simulating the performance of the antenna of FIGS. **1***a* and **3***a*.

FIG. **4***c* is a graph showing an input reactance determined by simulating the performance of the antenna of FIGS. **1***a* and **3***a*.

FIG. **5***a* is a perspective view of a top-loaded conical antenna including a plurality of shorting arms and a rectangular ground plane slot in accordance with an illustrative embodiment.

FIG. **5***b* is a top view of the top-loaded conical antenna of FIG. **5***a* in accordance with an illustrative embodiment.

FIG. **6** is a perspective view of the top-loaded conical antenna of FIG. **5***a* showing equivalent circuit elements for each part in accordance with an illustrative embodiment.

FIG. **7***a* is a graph showing a VSWR determined by simulating the performance of the antenna of FIGS. **3***a* and **5***a*.

FIG. **7***b* is a graph showing an input resistance determined by simulating the performance of the antenna of FIGS. **3***a* and **5***a*.

FIG. **7***c* is a graph showing an input reactance determined by simulating the performance of the antenna of FIGS. **3***a* and **5***a*.

FIG. **8** depicts a lumped matching network of a feed network of an antenna in accordance with an illustrative embodiment.

FIG. **9***a* is a graph showing a VSWR determined by simulating the performance of the antenna of FIG. **5***a* using the lumped matching network of FIG. **8**.

FIG. **9***b* is a graph showing a realized gain determined by simulating the performance of the antenna of FIG. **5***a* using the lumped matching network of FIG. **8**.

FIG. **9***c* is a graph showing an antenna efficiency determined by simulating the performance of the antenna of FIG. **5***a* using the lumped matching network of FIG. **8**.

FIGS. **10***a* and **10***b* depict graphs showing directional radiation patterns in the azimuth plane at different frequencies obtained by simulating the performance of the antenna of FIG. **5***a* using the lumped matching network of FIG. **8**.

FIGS. **11***a* and **11***b* depict graphs showing directional radiation patterns in the x-z elevation plane at different frequencies obtained by simulating the performance of the antenna of FIG. **5***a* using the lumped matching network of FIG. **8**.

FIGS. **12***a* and **12***b* depict graphs showing directional radiation patterns in the y-z elevation plane at different frequencies obtained by simulating the performance of the antenna of FIG. **5***a*.

FIG. **13** is a perspective view of a top-loaded conical antenna including a plurality of shorted arms and a circular ground plane slot in accordance with an illustrative embodiment.

FIG. **14** is a graph showing a VSWR determined by simulating the performance of the antenna of FIGS. **5***a* and **13**.

FIG. **15** is a graph showing a comparison between a VSWR determined by simulating the performance of the antenna of FIG. **5***a* and measuring a VSWR using a fabricated prototype of the antenna of FIG. **5***a*.

FIG. **16***a* is a perspective view of a top-loaded conical antenna including a plurality of shorting arms and a ground plane slot in accordance with a second illustrative embodiment.

FIG. **16***b* is a top view of the top-loaded conical antenna of FIG. **16***a* in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

With reference to FIG. **1***a*, a perspective view of an antenna **100** is shown in accordance with an illustrative embodiment. Antenna **100** may include a ground plane substrate **102**, a top hat conductor **104**, a feed conductor **106**, and a feed element **108**. Ground plane substrate **102** is electrically grounded and may be formed of any material suitable for forming an electrical ground for antenna **100**. For example, ground plane substrate **102** may be formed of a metal sheet alone or with a dielectric or magnetic material or a magneto-dielectric material on a top surface of the metal sheet. Ground plane substrate **102** is generally planar and defines a first plane. To describe the orientation of the components of antenna **100**, a coordinate reference system x-y-z is included in FIG. **1***a*. Based on the defined coordinate reference system x-y-z, the first plane is the x-y plane.

Though the assumption is made that ground plane substrate **102** is an infinite ground plane, in general, if ground plane substrate **102** is just slightly larger than top hat conductor **104**, antenna **100** is still effective as a radiator. For example, ground plane substrate **102** larger by a factor of 1.5 times than top hat conductor **104** is still effective as a radiator. In illustrative embodiment, ground plane substrate **102** is a metal sheet.

With reference to FIG. **1***b*, a top view of antenna **100** is shown in accordance with an illustrative embodiment. In an illustrative embodiment, top hat conductor **104** is generally planar and oriented in a second plane that is approximately parallel to the first plane defined by ground plane substrate **102**. Thus, top hat conductor **104** is oriented parallel to the x-y plane at a height **118** above ground plane substrate **102**. Top hat conductor **104** may be formed of any conducting material suitable for forming a radiator of antenna **100**.

In an illustrative embodiment, height **118** is approximately 100 millimeters (mm). In the illustrative embodiment, top hat conductor **104** has a rectangular shape when projected into the x-y plane. In alternative embodiments, top hat conductor **104** may form other polygonal, circular, or elliptical shapes when projected into the x-y plane. In the illustrative embodiment, top hat conductor **104** has a length **112** in the y-direction and a width **114** in the x-direction. Length **112** and width **114** define a diagonal **116**. In an illustrative embodiment, length **112** and width **114** define are approximately 200 mm though other dimensions may be used depending on the application environment for antenna **100**.

With reference to FIG. **1** *c*, a side view of feed conductor **106** is shown in accordance with an illustrative embodiment. Feed conductor **106** is electrically connected to feed element **108**. Feed element **108** is positioned approximately at a center of ground plane substrate **102** as shown with reference to FIG. **1***b*. In an illustrative embodiment, feed element **108** is a short length of coaxial cable including an inner connector **109** electrically coupled to a point on feed conductor **106** and an outer conductor **110** electrically coupled to ground plane substrate **102**.

In the illustrative embodiment of FIG. **1** *c*, feed conductor **106** is generally planar and oriented in a third plane that is approximately perpendicular to the first plane defined by ground plane substrate **102**. Feed conductor **106** may be formed of any conducting material suitable for forming a radiator of antenna **100**.

Feed conductor **106** includes a top edge **120**, a first side edge **122**, a second side edge **124**, a third side edge **126**, a fourth side edge **128**, and a bottom edge **130**. Top edge **120** of feed conductor **106** is electrically coupled to top hat conductor **104** along diagonal **116** of top hat conductor **104** as shown with reference to FIGS. **1***a* and **1***b*. In an illustrative embodiment, top edge **120** of feed conductor **106** is shorter than diagonal **116** of top hat conductor **104** though the difference is not readily visible in FIG. **1***b*. As a result, feed conductor **106** is positioned between ground plane substrate **102** and top hat conductor **104**.

Top edge **120** and bottom edge **130** are generally parallel. First side edge **122** extends generally perpendicularly from a first end of top edge **120**. Second side edge **124** extends between first side edge **122** and a first end of bottom edge **130**. Third side edge **126** extends generally perpendicularly from a second end of top edge **120**. Fourth side edge **128** extends between third side edge **126** and a second end of bottom edge **130**. Thus, first side edge **122** and second side edge **124** form a first side of feed conductor **106**, and third side edge **126** and fourth side edge **128** form a second side of feed conductor **106**. In the illustrative embodiment, feed conductor **106** is primarily cone shaped. In alternative embodiment, feed conductor **106** may not include first side edge **122** or third side edge **126** and/or bottom edge **130** resulting in a triangular shape. In an illustrative embodiment, feed conductor **106** forms essentially a monopole antenna and can be used to tune and adjust the resonances that result from the monopole structure. These resonances can be optimized such that they merge with the other resonances to form an ultra-wideband antenna. Thus, the shape of feed conductor **106** can be optimized to increase the bandwidth of antenna **100**.

With reference to FIG. **2***a*, a graph is provided that shows a voltage standing wave ratio (VSWR) at feed element **108** determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for top edge **120** of feed conductor **106**. A first VSWR curve **200** shows a VSWR as a function of transmit frequency that results for top edge **120** having a value equal to 55 mm. A second VSWR curve **202** shows a VSWR as a function of transmit frequency that results top edge **120** having a value equal to 140 mm. A third VSWR curve **204** shows a VSWR as a function of transmit frequency that results for top edge **120** having a value equal to 255 mm.

With reference to FIG. **2***b*, a graph is provided that shows an input resistance (real part of the impedance) determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for top edge **120** of feed conductor **106**. A first resistance curve **210** shows a resistance as a function of transmit frequency that results for top edge **120** having a value equal to 55 mm. A second resistance curve **212** shows a resistance as a function of transmit frequency that results for top edge **120** having a value equal to 140 mm. A third resistance curve **214** shows a resistance as a function of transmit frequency that results for top edge **120** having a value equal to 255 mm.

With reference to FIG. **2***c*, a graph is provided that shows an input reactance (imaginary part of the impedance) determined by simulating the performance of the antenna of FIG. **1***a* with different dimensions for top edge **120** of feed conductor **106**. A first reactance curve **220** shows a reactance as a function of transmit frequency that results for top edge **120** having a value equal to 55 mm. A second reactance curve **222** shows a reactance as a function of transmit frequency that results for top edge **120** having a value equal to 140 mm. A third reactance curve **224** shows a reactance as a function of transmit frequency that results for top edge **120** having a value equal to 255 mm.

Antenna **100** is a potentially broadband antenna that is primarily a capacitive antenna in which the parallel capacitance between top hat conductor **104** and ground plane substrate **102** is the dominant factor. The magnitude of the parallel capacitance is directly related to the area of top hat conductor **104**. To achieve a low frequency of operation, the dimensions of top hat conductor **104** are maximized in view of the dimensional constraints that result based on the application environment for antenna **100**. The performance of antenna **100** is examined using full-wave electromagnetic wave (EM) simulations, and the side dimensions of feed conductor **106** are optimized to achieve the lowest VSWR possible over as wide a frequency band as possible.

With reference to FIG. **3***a*, a perspective view of a second antenna **300** is shown in accordance with an illustrative embodiment. Second antenna **300** may include ground plane substrate **102**, top hat conductor **104**, feed conductor **106**, feed element **108**, a first shorting arm **302**, and a second shorting arm **304**. A greater or a fewer number of shorting arms may be included in alternative embodiments. In the illustrative embodiment, first shorting arm **302** and second shorting arm **304** are generally planar sheets and rectangular in shape when projected into the x-y, y-z, or x-z planes though other shapes may be used. For example, first shorting arm **302** and second shorting arm **304** may form other polygonal, circular, or elliptical shapes when projected into the x-y, y-z, or x-z planes. First shorting arm **302** and second shorting arm **304** further need not be formed of generally planar sheets.

First shorting arm **302** is electrically coupled to top hat conductor **104** and to ground plane substrate **102** as shown with reference to FIG. **3***b*. Second shorting arm **304** is also electrically coupled to top hat conductor **104** and to ground plane substrate **102** as shown with reference to FIG. **3***b*. First shorting arm **302** and second shorting arm **304** may be formed of any conducting material suitable for forming a radiator of antenna **100**. The material used to form first shorting arm **302** and second shorting arm **304** may be the same or different from each other. The material used to form first shorting arm **302** and second shorting arm **304** may be the same or different from that used to form top hat conductor **104** and/or feed conductor **106**. The material used to form top hat conductor **104** and feed conductor **106** may be the same or different from each other. In an illustrative embodiment, first shorting arm **302** and second shorting arm **304** may carry relatively strong current densities. To avoid ohmic losses that could adversely impact the performance of antenna **100**, good conductors may be used to form first shorting arm **302** and second shorting arm **304**.

First shorting arm **302** includes a top edge **306**, a first side edge **308**, a second side edge **310**, and a bottom edge **312**. First shorting arm **302** is electrically coupled to top hat conductor **104** along top edge **306**. Top edge **306** is positioned in a first corner of top hat conductor **104**. First shorting arm **302** is electrically coupled to ground plane substrate **102** along bottom edge **312**. Top edge **306** and bottom edge **312** of first shorting arm **302** are generally parallel.

Second shorting arm **304** includes a top edge **316**, a first side edge **318**, a second side edge **320**, and a bottom edge **322**. Second shorting arm **304** is electrically coupled to top hat conductor **104** along top edge **316**. Top edge **316** of second shorting arm **304** is positioned in a second corner of top hat conductor **104**. Second shorting arm **304** is electrically coupled to ground plane substrate **102** along bottom edge **322** of second shorting arm **304**. Top edge **316** and bottom edge **322** of second shorting arm **304** are generally parallel. Feed conductor **106** extends between the remaining corners of top hat conductor **104**. Thus, first shorting arm **302** and second shorting arm **304** are positioned in opposite corners of top hat conductor **104** on either side of feed conductor **106**.

One drawback of adding first shorting arm **302** and second shorting arm **304** to antenna **100** to form second antenna **300** is that the shorting arms are solely responsible for the radiation characteristics at low frequencies, while at higher frequencies they act as an array antenna and can produce undesirable nulls in the radiation patterns. To ensure the antenna maintains consistent omnidirectional radiation patterns across its entire frequency band, the shorting arms are positioned so that the shorting arms are rotationally symmetric. Thus, first shorting arm **302** and second shorting arm **304** extend from top hat conductor **104** and from ground plane substrate **102** at an angle **324** and are positioned to be rotationally symmetric. In an illustrative embodiment, angle **324** is between 10 and 90 degrees. In an alternative embodiment, angle **324** may be approximately zero if first shorting arm **302** and second shorting arm **304** are curved. Considering the currents on shorting arm **302** and second shorting arm **304**, this method distributes the currents more symmetrically around antenna **100** and improves the omindirectionality at higher frequencies.

Top edge **306** and bottom edge **312** of first shorting arm **302** and top edge **316** and bottom edge **322** of second shorting arm **304** have a width **326**. First side edge **308** and second side edge **310** of first shorting arm **302** and first side edge **318** and second side edge **320** of second shorting arm **304** have a length **328**. As a result, first shorting arm **302** and second shorting arm **304** have a projected length **330** when projected into the x-y plane as shown with reference to FIGS. **3***b* and **3***c*. Of course, first shorting arm **302** and second shorting arm **304** may be oriented in other directions. For example, bottom edge **312** of first shorting arm **302** and bottom edge **322** of second shorting arm **304** may be rotated from zero to 90 degrees in the x-y plane. In an illustrative embodiment, width **326** is approximately 30 mm and length **328** is approximately 122 mm though other dimensions may be used depending on the application environment for antenna **100**.

With reference to FIG. **4***a*, a graph is provided that shows a VSWR at feed element **108** determined by simulating the performance of the antenna of FIG. **3***a*. A fourth VSWR curve **400** shows a VSWR as a function of transmit frequency that results by including first shorting arm **302** and second shorting arm **304** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Third VSWR curve **204** is included in the graph for comparison.

With reference to FIG. **4***b*, a graph is provided that shows an input resistance determined by simulating the performance of the antenna of FIG. **3***a*. A fourth resistance curve **410** shows a resistance as a function of transmit frequency that results by including first shorting arm **302** and second shorting arm **304** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Third resistance curve **214** is included in the graph for comparison.

With reference to FIG. **4***c*, a graph is provided that shows an input reactance determined by simulating the performance of the antenna of FIG. **3***a*. A fourth reactance curve **420** shows a reactance as a function of transmit frequency that results by including first shorting arm **302** and second shorting arm **304** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Third reactance curve **224** is included in the graph for comparison.

The addition of one or more shorting arms results in addition of a parallel inductance. The value of the parallel inductance increases by increasing length **328** or decreasing width **326** of first shorting arm **302** and second shorting arm **304**. The parallel inductance due to first shorting arm **302** and second shorting arm **304** and the parallel capacitance due to top hat conductor **104** and ground plane substrate **102** provide a potential parallel resonance below the minimum frequency of operation of antenna **100**. The placement, the size, and the shape of the shorting arms have a significant effect on the antenna impedance (resistance and reactance). The shorting arms are designed and optimized such that the introduced additional resonance is close to the minimum desired operating frequency of antenna **100**, so they can merge together to achieve an ultra-wideband (UWB) structure.

With reference to FIG. **5***a*, a perspective view of a third antenna **500** is shown in accordance with an illustrative embodiment. Third antenna **500** may include ground plane substrate **102**, top hat conductor **104**, feed conductor **106**, feed element **108**, first shorting arm **302**, second shorting arm **304**, and a ring slot **502**. In the illustrative embodiment, ring slot **502** is a rectangular slot formed in ground plane substrate **102**. For example, ring slot **502** may be etched or milled into ground plane substrate **102**. Ring slot **502** is symmetrically positioned to surround feed element **108**. In alternative embodiments, ring slot **502** may be positioned asymmetrically relative to feed element **108**. Ring slot **502** may form other polygonal, circular, or elliptical shapes in the x-y plane.

For simplicity in fabrication, a dielectric material with a top surface formed of a metal sheet is used as ground plane substrate **102**, and ring slot **502** is formed by etching of ground plane substrate **102**. The dielectric constant of ground plane substrate **102** can change the value of capacitance formed by ring slot **502**. To minimize the effect of the material, a low dielectric material can be used as ground plane substrate **102**.

In an illustrative embodiment, ring slot **502** has a slot width **504**, a width **506** in the x-direction, and a length **508** in the y-direction. In an illustrative embodiment, slot width **504** is approximately 7 mm, width **506** is approximately 203 mm, and length **508** is approximately 203 mm though other dimensions may be used depending on the application of antenna **100**, and of course, the other dimensions of the components of third antenna **500**. Ring slot **502** does not radiate in the band of interest; instead, ring slot **502** acts as a series capacitance. The value of the series capacitance increases by decreasing width **506** of ring slot **502** or by decreasing slot width **504** of ring slot **502**. The values for slot width **504** and width **506** may be chosen by examining the effect of these two parameters on VSWR, input impedance, and input reactance of antenna **100** to reduce the quality factor of the additional resonance and achieve an impedance match across the entire band.

With reference to FIG. **6**, the effect of top hat conductor **104** is modeled as a parallel capacitance **600**, the effect of first shorting arm **302** and second shorting arm **304** is modeled as a parallel inductance **602**, and the effect of ring slot **502** is modeled as a series capacitance **604**. Third antenna **500** can be designed using the equivalent circuit model illustrated in FIG. **6** and full wave EM simulation. The placement, mounting angle, and shape of first shorting arm **302** and second shorting arm **304** and the placement and shape of ring slot **502** have a significant effect on the impedance of third antenna **500**. These characteristics are designed and optimized using full wave EM simulation such that the impedance is well-matched and centered on the Smith chart used for analysis of impedance matching.

With reference to FIG. **7***a*, a graph is provided that shows a VSWR at feed element **108** determined by simulating the performance of the antenna of FIG. **5***a*. A fifth VSWR curve **700** shows a VSWR as a function of transmit frequency that results by including ring slot **502** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Fourth VSWR curve **400** is included in the graph for comparison.

With reference to FIG. **7***b*, a graph is provided that shows an input resistance determined by simulating the performance of the antenna of FIG. **5***a*. A fifth resistance curve **710** shows a resistance as a function of transmit frequency that results by including ring slot **502** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Fourth resistance curve **410** is included in the graph for comparison.

With reference to FIG. **7***c*, a graph is provided that shows an input reactance determined by simulating the performance of the antenna of FIG. **5***a*. A fifth reactance curve **720** shows a reactance as a function of transmit frequency that results by including ring slot **502** with the illustrative dimensions and with top edge **120** having a value equal to 255 mm. Fourth reactance curve **420** is included in the graph for comparison.

As shown in FIGS. **7***a*-**7***c*, series capacitance **604** helps to decrease the quality factor of the additional resonance, which results in achieving an impedance match across the entire band. The placement and the width of the slot have a significant effect on the capacitance value. The value of the series capacitance increases by decreasing the radius or width **506** of ring slot **502** or by decreasing the radius or slot width **504** of ring slot **502**.

To obtain the maximum bandwidth available, the transmission and reflection coefficients of third antenna **500** should be unity inside and outside of the band of interest, respectively. With reference to FIG. **8**, a feed network **812** is shown in accordance with an illustrative embodiment. Feed network **812** may include a first inductor **802**, a first capacitor **804**, a second inductor **806**, and a second capacitor **808**. First inductor **802** and first capacitor **804** are mounted in series between a port **800** and ground plane substrate **102**. Second inductor **806** and second capacitor **808** are mounted in series between first inductor **802** and ground plane substrate **102**. Feed element **108** is electrically coupled between second inductor **806** and second capacitor **808**.

Feed network **812** forms a lumped matching network circuit designed to match the transmission and reflection coefficients of third antenna **500**. The values of first inductor **802**, first capacitor **804**, second inductor **806**, and second capacitor **808** are designed and optimized to achieve an impedance match to third antenna **500** across the entire frequency range. Thus, feed network **812** is coupled to receive a radio frequency (RF) alternating current (AC) signal and to form an impedance matched signal output on feed element **108** for radiation from third antenna **500**.

With reference to FIG. **8**, a transmitter and/or receiver or transceiver **810** includes port **800**, feed network **812**, and third antenna **500** in accordance with an illustrative embodiment. The RF AC signal is provided to port **800** from a signal processor (not shown). Feed network **812** is coupled to port **800** to receive the RF AC signal and to form a matched signal output through feed element **108** for radiation from third antenna **500**. Feed network **812** is coupled to feed element **108** to receive a second RF AC signal received by third antenna **500** and to form a matched signal output through port **800** to the signal processor.

With reference to FIG. **9***a*, a graph is provided that shows a VSWR at feed element **108** determined by simulating the performance of third antenna **500** with the illustrative dimensions (top edge **120** having a value equal to 255 mm) and using feed network **812**. In the illustrative embodiment, an inductance value for first inductor **802** was 5.25 nanoHenry (nH), a capacitance value for first capacitor **804** was 2.2 picoFarads (pF), an inductance value for second inductor **806** was 4.4 nH, and a capacitance value for second capacitor **808** was 1.6 pF. A sixth VSWR curve **900** shows a resulting VSWR as a function of transmit frequency.

With reference to FIG. **9***b*, a graph is provided that shows a realized gain of third antenna **500** determined by simulating the performance of third antenna **500** with the illustrative dimensions (top edge **120** having a value equal to 255 mm). A gain curve **902** shows a resulting realized gain as a function of transmit frequency.

With reference to FIG. **9***c*, a graph is provided that shows an efficiency of third antenna **500** determined by simulating the performance of third antenna **500** with the illustrative dimensions (top edge **120** having a value equal to 255 mm). A first efficiency curve **904** shows a radiation efficiency as a function of transmit frequency using feed network **812**. A second efficiency curve **906** shows a total efficiency as a function of transmit frequency. As shown, third antenna **500** achieves a 3.8 dBi realized gain at the lowest frequency of operation and 5 dBi over most of the operating band. Over most of the operating band, the total efficiency remains above 90% though the total efficiency is approximately 65% at lower frequencies.

With reference to FIGS. **10***a* and **10***b*, graphs are provided that show directional radiation patterns in the x-y (azimuth) plane in the frequency range of 0.2-1.4 gigahertz (GHz). The results were obtained by simulating the performance of third antenna **500**. A first curve **1000** shows the representative response at a frequency of 0.2 GHz; a second curve **1002** shows the representative response at a frequency of 0.4 GHz; a third curve **1004** shows the representative response at a frequency of 0.6 GHz; a fourth curve **1006** shows the representative response at a frequency of 0.8 GHz; a fifth curve **1008** shows the representative response at a frequency of 1.0 GHz; a sixth curve **1010** shows the representative response at a frequency of 1.2 GHz; and a seventh curve **1012** shows the representative response at a frequency of 1.4 GHz.

With reference to FIGS. **11***a* and **11***b*, graphs are provided that show directional radiation patterns showing directional radiation patterns in the x-z elevation plane in the frequency range of 0.2-1.4 gigahertz (GHz). A first curve **1100** shows the representative response at a frequency of 0.2 GHz; a second curve **1102** shows the representative response at a frequency of 0.4 GHz; a third curve **1104** shows the representative response at a frequency of 0.6 GHz; a fourth curve **1106** shows the representative response at a frequency of 0.8 GHz; a fifth curve **1108** shows the representative response at a frequency of 1.0 GHz; a sixth curve **1110** shows the representative response at a frequency of 1.2 GHz; and a seventh curve **1112** shows the representative response at a frequency of 1.4 GHz.

With reference to FIGS. **12***a* and **12***b*, graphs are provided that show directional radiation patterns showing directional radiation patterns in the y-z elevation plane in the frequency range of 0.2-1.4 gigahertz (GHz). A first curve **1200** shows the representative response at a frequency of 0.2 GHz; a second curve **1202** shows the representative response at a frequency of 0.4 GHz; a third curve **1204** shows the representative response at a frequency of 0.6 GHz; a fourth curve **1206** shows the representative response at a frequency of 0.8 GHz; a fifth curve **1208** shows the representative response at a frequency of 1.0 GHz; a sixth curve **1210** shows the representative response at a frequency of 1.2 GHz; and a seventh curve **1212** shows the representative response at a frequency of 1.4 GHz.

The simulated results demonstrate that third antenna **500** provides monopole-like omnidirectional radiation patterns over the entire frequency band of interest. Additionally, third antenna **500** using feed network **812** of FIG. **8** achieves a VSWR lower than 2:1 over a 7.5:1 bandwidth. For third antenna **500**, the value of the comparison factor is 27.6, which is more than twice that of the Goubau antenna as a standard small wideband antenna. As a result, third antenna **500** provides a better design in terms of the bandwidth-to-size ratio. At the lowest frequency of operation, third antenna **500** using feed network **812** of FIG. **8** has electrical dimensions of $0.065\lambda_{min}\times0.13\lambda_{min}\times0.13\lambda_{min}$, where λ_{min} is the free space wavelength at the lowest frequency of operation ~0.2 GHz.

With reference to FIG. **13**, a perspective view of a fourth antenna **1300** is shown in accordance with an illustrative embodiment. Fourth antenna **1300** may include ground plane substrate **102**, top hat conductor **104**, feed conductor **106**, feed element **108**, first shorting arm **302**, second shorting arm **304**, and a second ring slot **1302**. In the illustrative embodiment, second ring slot **1302** is a circular slot formed in ground plane substrate **102**. Second ring slot **1302** is symmetrically positioned to surround feed element **108**. In an illustrative embodiment, second ring slot **1302** has slot width **504**. In an illustrative embodiment, slot width **504** is approximately 7 mm and a diameter of second ring slot **1302** is approximately 203 mm though other dimensions may be used depending on the application of antenna **100**, and of course, the other dimensions of the components of third antenna **500**.

With reference to FIG. **14**, a graph is provided that shows a VSWR at feed element **108** determined by simulating the performance of fourth antenna **1300** with the illustrative dimensions. A sixth VSWR curve **1400** shows a VSWR as a function of transmit frequency that results by including ring slot **1302** with top edge **120** having a value equal to 255 mm. Fourth VSWR curve **400** is included in the graph for comparison.

A prototype of third antenna **500** was fabricated. The prototype was scaled down by a factor of three for simplicity. Thus, the operating frequencies of the antenna scale up by the same factor of three. Feed network **812** was not considered. With reference to FIG. **15**, a graph is provided that shows a VSWR at feed element **108** generated by the prototype. A seventh VSWR curve **1500** shows a VSWR as a function of transmit frequency generated by the prototype. An eighth VSWR curve **1502** shows a VSWR as a function of transmit frequency determined by simulating the scaled version of the antenna. Eighth VSWR curve **1502** is included in the graph for comparison. The prototype results compare favorably with the simulated results. In the fabricated prototype, Rogers 5880 material with a dielectric constant of 2.2 was used to form ground plane substrate **102**.

With reference to FIG. **16***a*, a perspective view of a fifth antenna **1600** is shown in accordance with an illustrative embodiment. Fifth antenna **1600** may include ground plane substrate **102**, top hat conductor **104**, a feed conductor **106**, a second feed conductor **1602**, feed element **108**, first shorting arm **302**, second shorting arm **304**, a third shorting arm **1604**, a fourth shorting arm **1606**, and ring slot **502**. In the illustrative embodiment, second feed conductor **1604** has the same shape as feed conductor **106**. In the illustrative embodiment of FIG. **16***a*, first feed conductor **106** is positioned along a center of top hat conductor **104** parallel to the y-z plane, and second feed conductor **1602** is positioned along a center of top hat conductor **104** parallel to the x-z plane.

With reference to the illustrative embodiment of FIGS. **16***a* and **16***b*, first shorting arm **302** extends from top hat conductor **104** adjacent a first end **1608** of feed conductor **106**, second shorting arm **304** extends from top hat conductor **104** adjacent a second end **1610** of feed conductor **106**, third shorting arm **1604** extends from top hat conductor **104** adjacent a first end **1612** of second feed conductor **1602**, and fourth shorting arm **1606** extends from top hat conductor **104** adjacent a second end **1614** of second feed conductor **1602**.

Using fifth antenna **1600** additional omnidirectionality can be achieved. However, a drawback of adding more feed conductors and shorting arms is an increase in the corresponding parallel inductance and, as a result, an increase in the minimum frequency of operation. Thus, fifth antenna **1600** can be used in applications in which omnidirectionality is a higher priority than lowest frequency of operation.

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, the use of “and” or “or” is intended to include “and/or” unless specifically indicated otherwise.

The foregoing description of illustrative embodiments of the invention has been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the invention 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 invention. The embodiments were chosen and described in order to explain the principles of the invention and as practical applications of the invention to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. An antenna comprising:

a ground plane substrate;

a feed conductor comprising a first end and a second end, wherein the first end is configured for electrical coupling to a feed network through a feed element extending from the ground plane substrate;

a top hat conductor comprising a generally planar sheet mounted to the second end of the feed conductor in a first plane approximately parallel to a second plane defined by the ground plane substrate;

a shorting arm comprising a third end and a fourth end, wherein the third end is mounted to the top hat conductor, and the fourth end is mounted to the ground plane substrate; and

a ring slot formed in the ground plane substrate around the feed element and configured to act as a series capacitance.

2. The antenna of claim **1**, wherein the top hat conductor forms a polygon when projected into the second plane.

3. The antenna of claim **2**, wherein the second end of the feed conductor is mounted along a diagonal of the polygon formed by the top hat conductor.

4. The antenna of claim **1**, wherein the top hat conductor forms a circle when projected into the second plane, and the second end of the feed conductor is mounted along a diameter of the circle formed by the top hat conductor.

5. The antenna of claim **1**, wherein the top hat conductor forms a rectangle when projected into the second plane.

6. The antenna of claim **5**, further comprising a second shorting arm comprising a fifth end and a sixth end, wherein the fifth end is mounted to the top hat conductor, and the sixth end is mounted to the ground plane substrate.

7. The antenna of claim **6**, wherein the second end of the feed conductor is mounted along a diagonal of the rectangle formed by the top hat conductor, the shorting arm is mounted to extend from a first corner of the rectangle that does not include the feed conductor, and the second shorting arm is mounted to extend from a second corner of the rectangle that does not include the feed conductor.

8. The antenna of claim **6**, wherein the shorting arm and the second shorting arm are generally planar sheets that extend from the top hat conductor and from the ground plane substrate at an angle in the range of 10 to 90 degrees.

9. The antenna of claim 6, further comprising:

a third shorting arm comprising a seventh end and an eighth end, wherein the seventh end is mounted to the top hat conductor, and the eighth end is mounted to the ground plane substrate; and

a fourth shorting arm comprising a ninth end and a tenth end, wherein the ninth end is mounted to the top hat conductor, and the tenth end is mounted to the ground plane substrate.

10. The antenna of claim 9, further comprising:

a second feed conductor comprising an eleventh end and a twelfth end, wherein the eleventh end is configured for electrical coupling to the feed network through the feed element;

wherein the top hat conductor is mounted to the twelfth end of the second feed conductor.

11. The antenna of claim 10, wherein the feed conductor is mounted along a first center line between a first pair of opposite sides of the rectangle, the second feed conductor is mounted along a second center line between a second pair of opposite sides of the rectangle, wherein the first pair of opposite sides and the second pair of opposite sides define the rectangle.

12. The antenna of claim 11, wherein the shorting arm is mounted to extend from a first end of the first center line of the top hat conductor, the second shorting arm is mounted to extend from a second end of the first center line of the top hat conductor, the third shorting arm is mounted to extend from a first end of the second center line of the top hat conductor, and the fourth shorting arm is mounted to extend from a second end of the second center line of the top hat conductor.

13. The antenna of claim 1, wherein the feed conductor is a generally planar sheet that extends generally perpendicularly relative to the second plane, further wherein the ring slot acts as the series capacitance between the shorting arm and the feed conductor.

14. The antenna of claim 13, wherein the feed conductor forms a polygon when projected into a plane that is perpendicular to the second plane.

15. The antenna of claim 14, wherein the polygon is primarily cone shaped.

16. The antenna of claim 1, wherein the shorting arm is a generally planar sheet that forms a polygon when projected into the second plane.

17. The antenna of claim 16, wherein the shorting arm forms a rectangle when projected into the second plane.

18. The antenna of claim 1, wherein the ring slot is centered around the feed element and positioned in the ground plane substrate between the feed element and the fourth end of the shorting arm.

19. A transmitter comprising:

a feed network comprising a matching network circuit coupled to receive a signal through a port and to form a matched signal output through a feed element; and

an antenna comprising

a ground plane substrate;

a feed conductor comprising a first end and a second end, wherein the first end is configured for electrical coupling to the matching network circuit through the feed element to receive the matched signal, wherein the feed element extends from the ground plane substrate;

a top hat conductor comprising a generally planar sheet mounted to the second end of the feed conductor in a first plane approximately parallel to a second plane defined by the ground plane substrate;

a shorting arm comprising a third end and a fourth end, wherein the third end is mounted to the top hat conductor, and the fourth end is mounted to the ground plane substrate; and

a ring slot formed in the ground plane substrate around the feed element and configured to act as a series capacitance;

wherein the matching network circuit is configured to impedance match the antenna.

20. The transmitter of claim 19, wherein the matching network circuit comprises a first inductor, a first capacitor, a second inductor, and a second capacitor, wherein the first inductor and the first capacitor are mounted in series between the port and the ground plane substrate, the second inductor and the second capacitor are mounted in series between the first inductor and the ground plane substrate, and the feed element is electrically coupled between the second inductor and the second capacitor.

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