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(54) ULTRA-WIDEBAND, LOW PROFILE ANTENNA

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(51) **Int. Cl.**

H01Q 11/12 (2006.01)
H01Q 7/00 (2006.01)
H01Q 21/00 (2006.01)

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

CPC ***H01Q 7/00*** (2013.01); ***H01Q 21/0006*** (2013.01)

(58) **Field of Classification Search**

CPC H01Q 7/00
USPC 343/741, 742, 855, 866, 867
See application file for complete search history.

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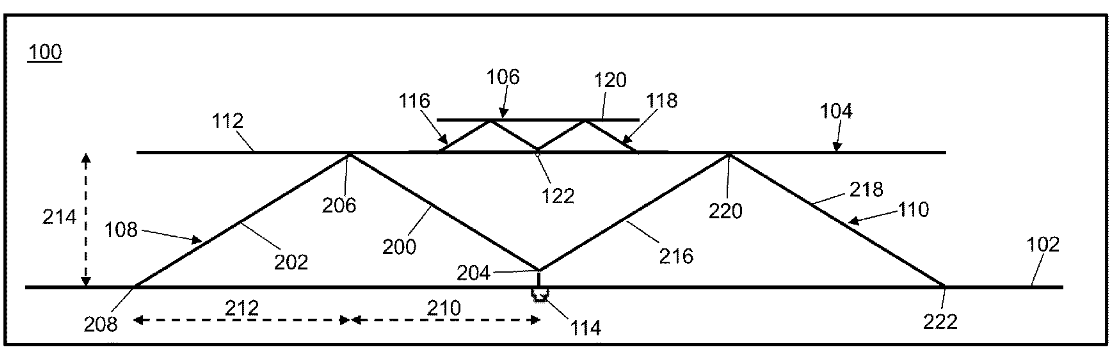
(57) **ABSTRACT**

An antenna system that includes a ground plane substrate, a first antenna, and a second antenna is provided. The first antenna includes a first loop conductor electrically connected to a feed network and to the ground plane substrate, a second loop conductor electrically connected to the feed network and to the ground plane substrate, and a first conductor mounted to and electrically connected to a first edge of the first loop conductor and to a second edge of the second loop conductor. The second antenna includes a third loop conductor electrically connected to the feed network and to the first conductor, a fourth loop conductor electrically connected to the feed network and to the first conductor, and a second conductor mounted to and electrically connected to a third edge of the third loop conductor and to a fourth edge of the fourth loop conductor.

20 Claims, 12 Drawing Sheets



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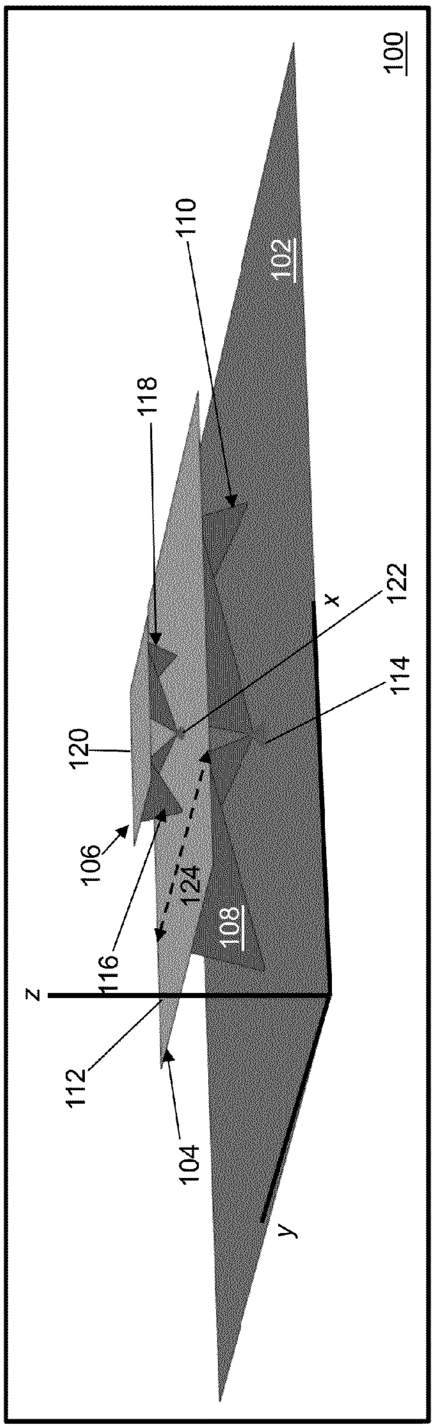
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x
y
z

Fig. 1

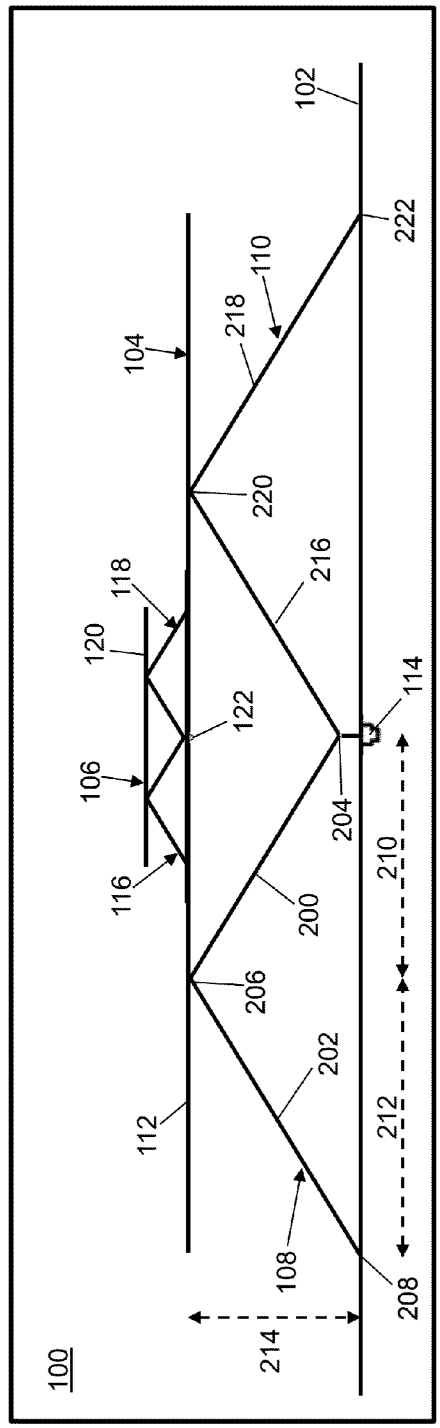
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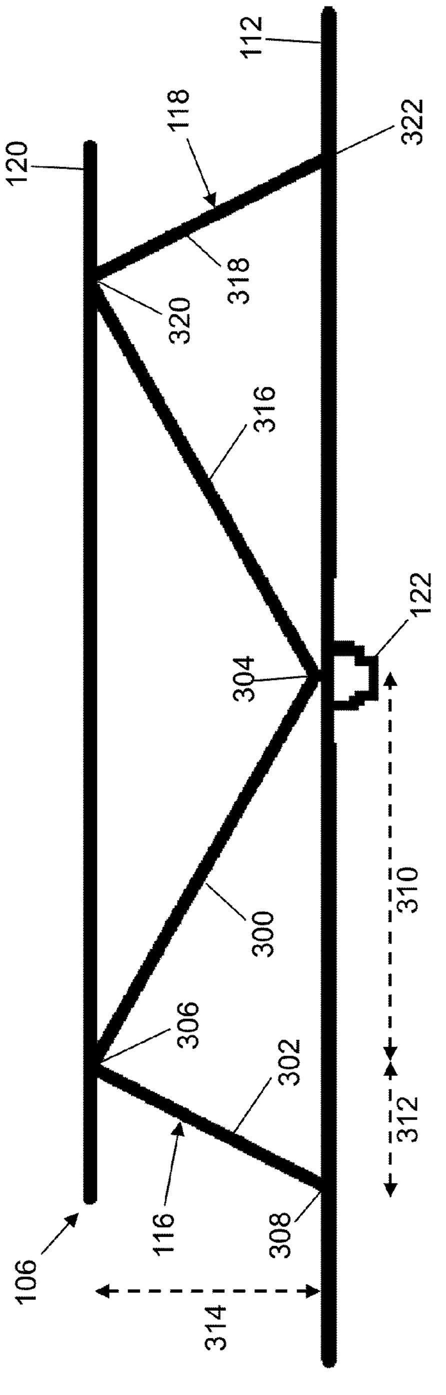
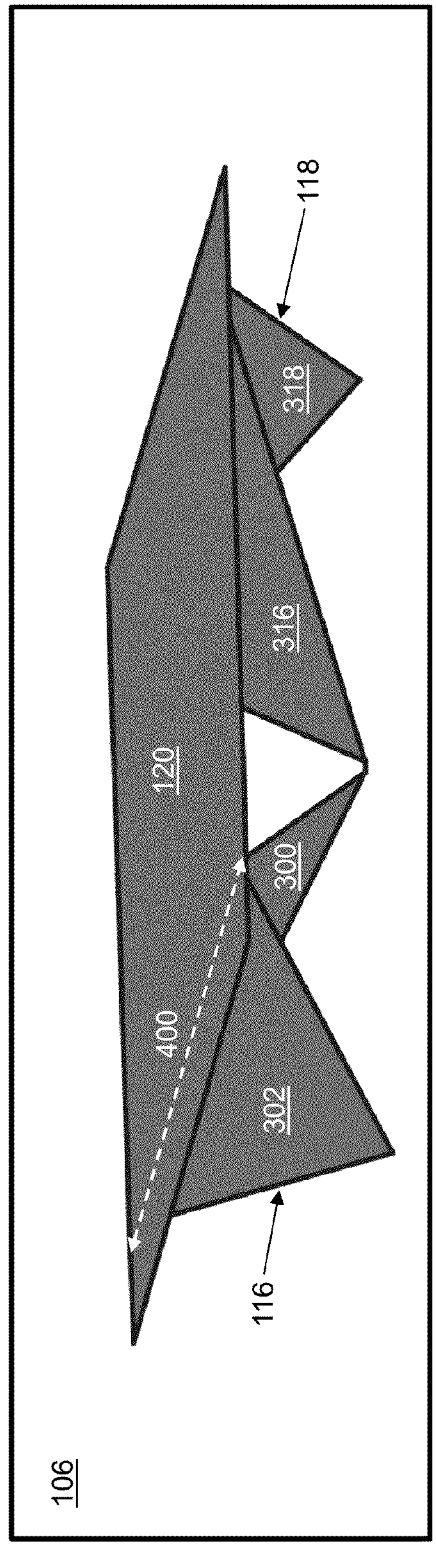
Fig. 2



112
120
118
322
320
318
316
122
304
300
306
302
310
312
106
116
308
314

Fig. 3



118
318
316
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300
400
302
116
106

Fig. 4

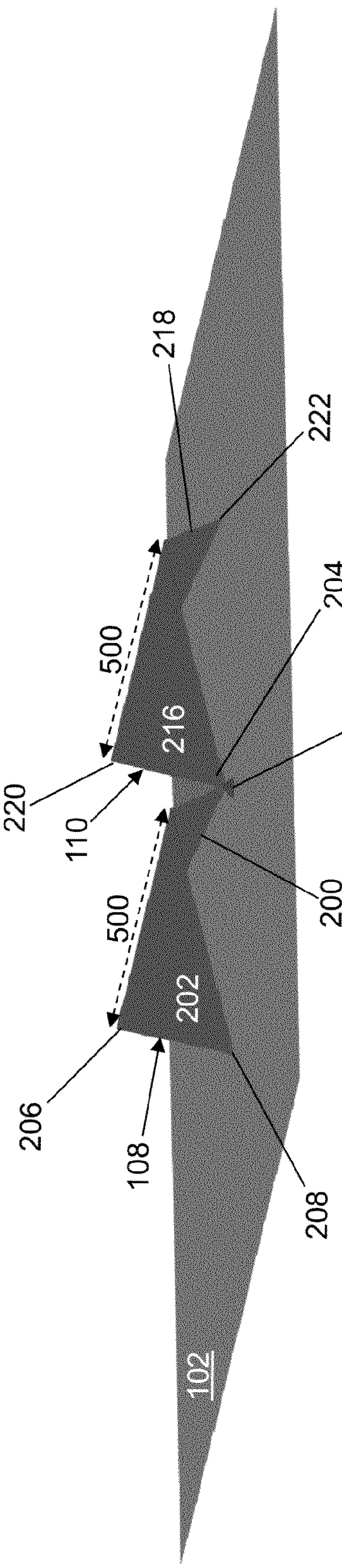
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Fig. 5

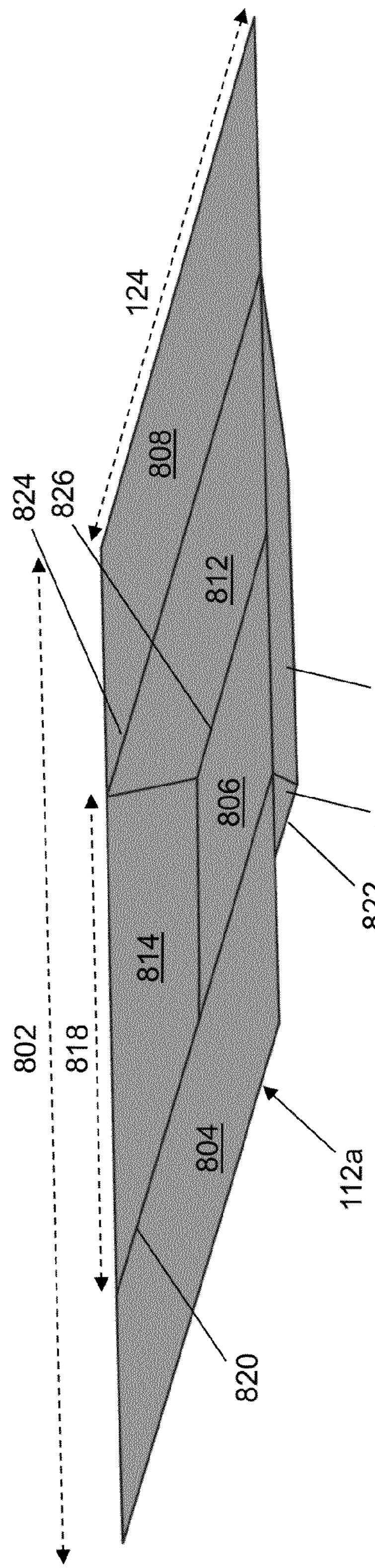
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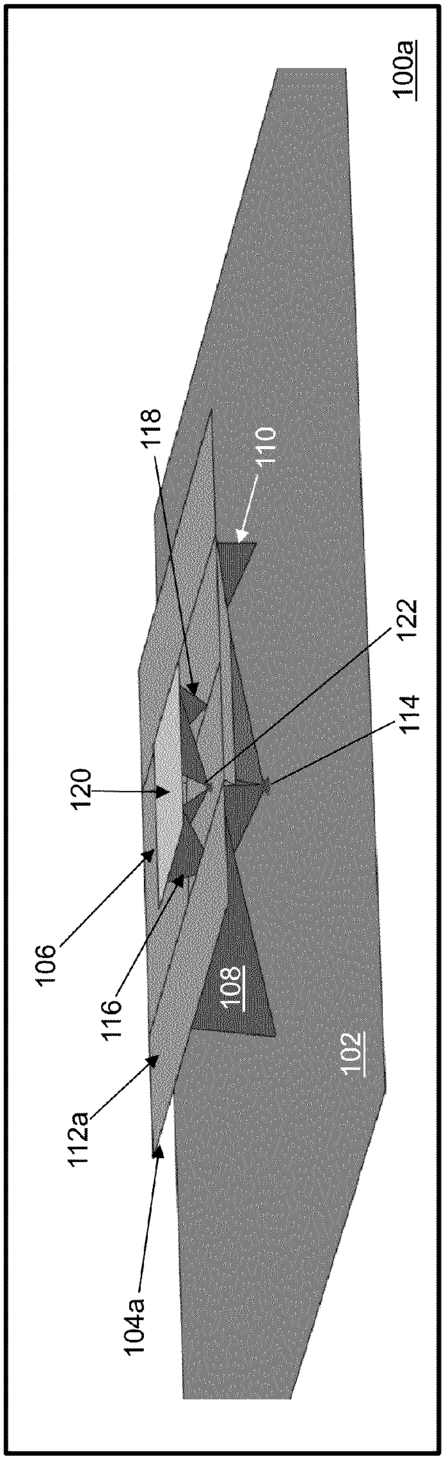
Fig. 8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112a
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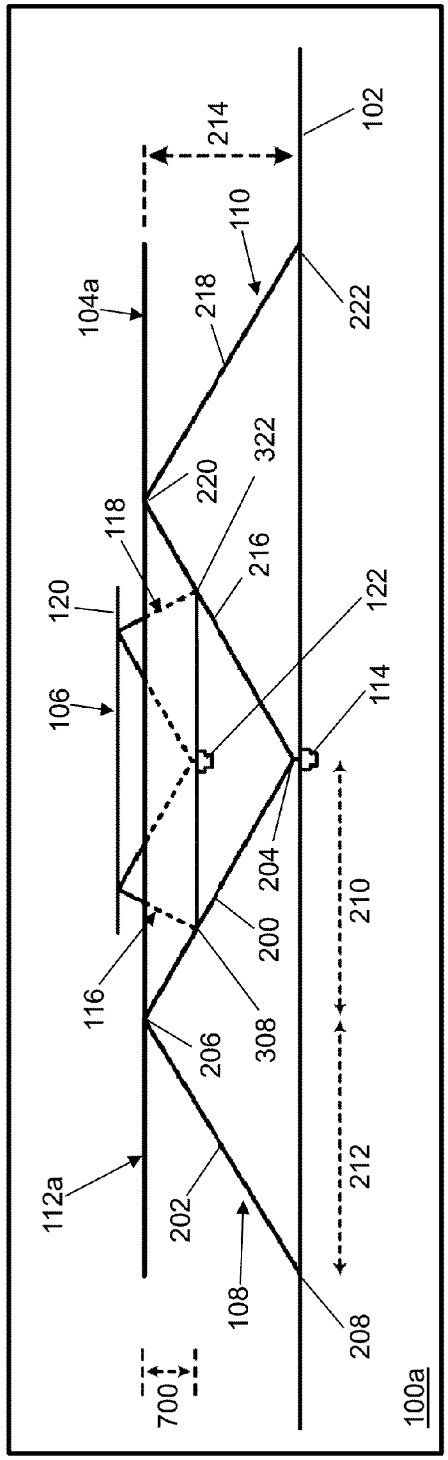
Fig. 6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112a
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202
108
208
700
100a

Fig. 7

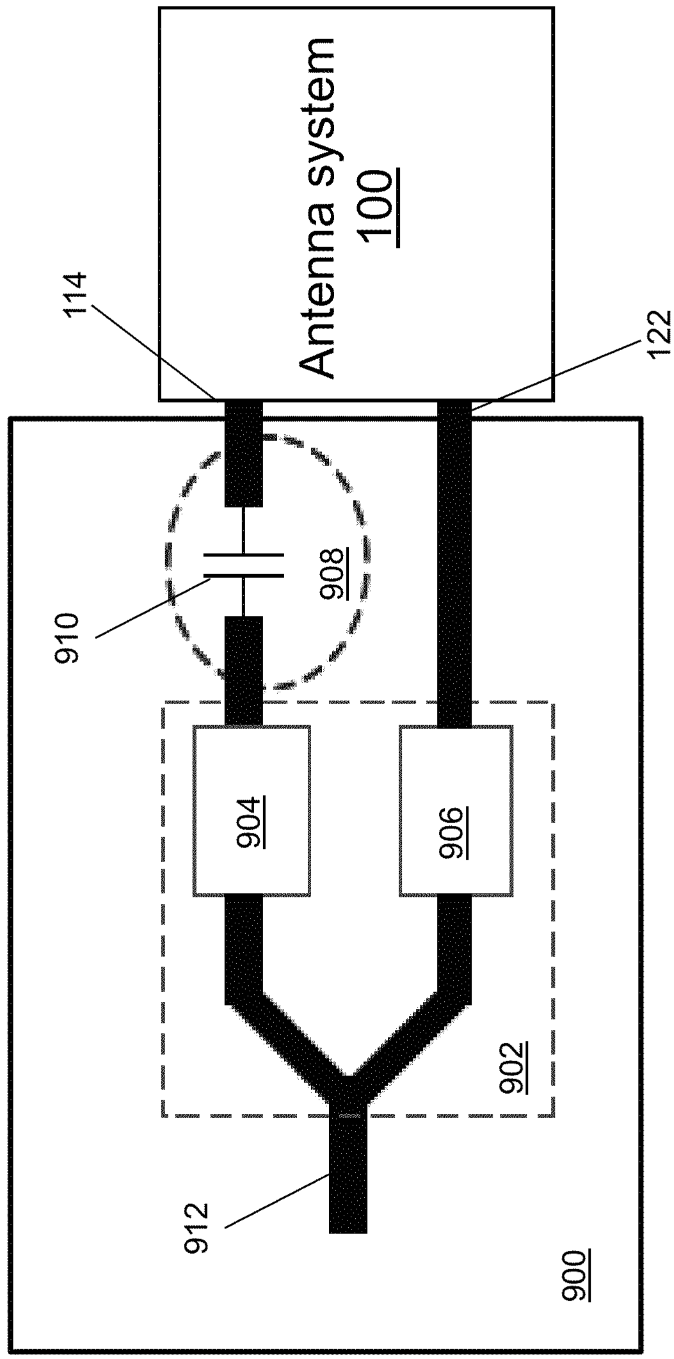


Fig. 9

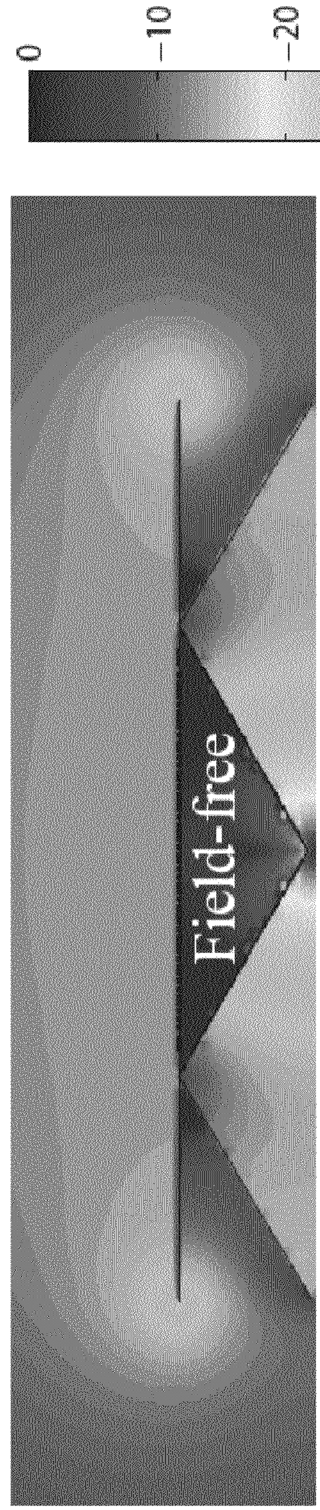


Fig. 10

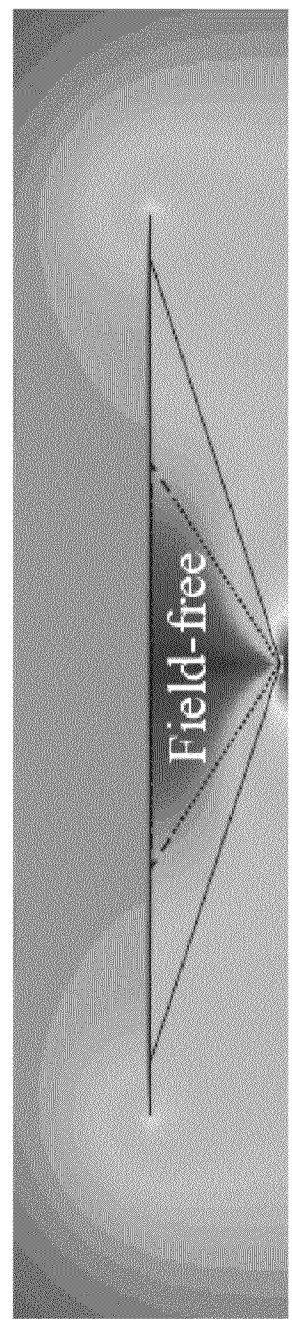
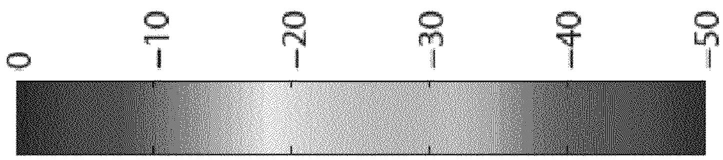


Fig. 11



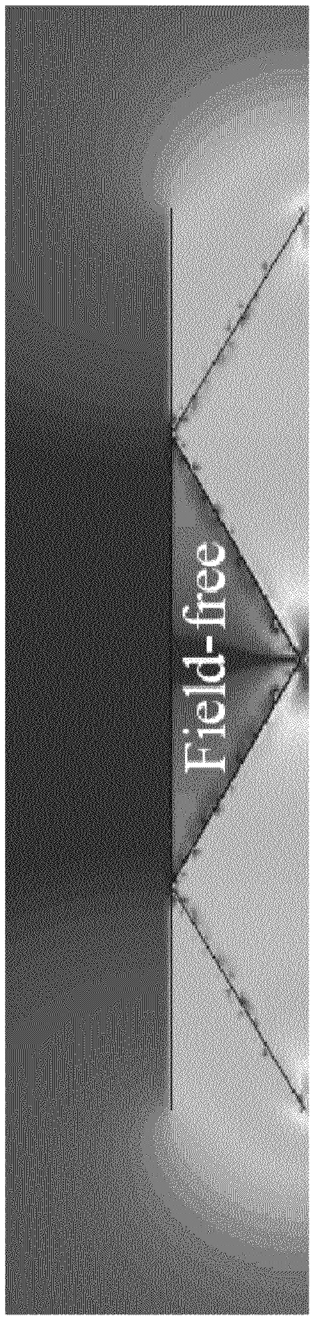


Fig. 12

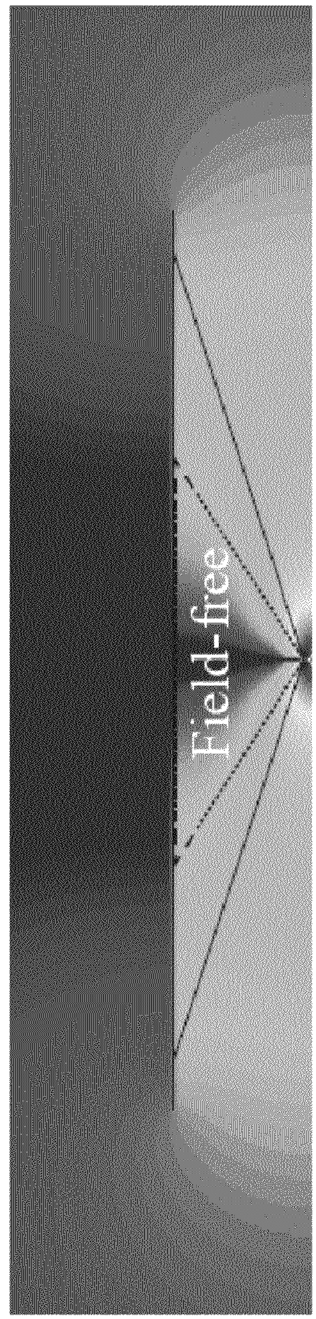
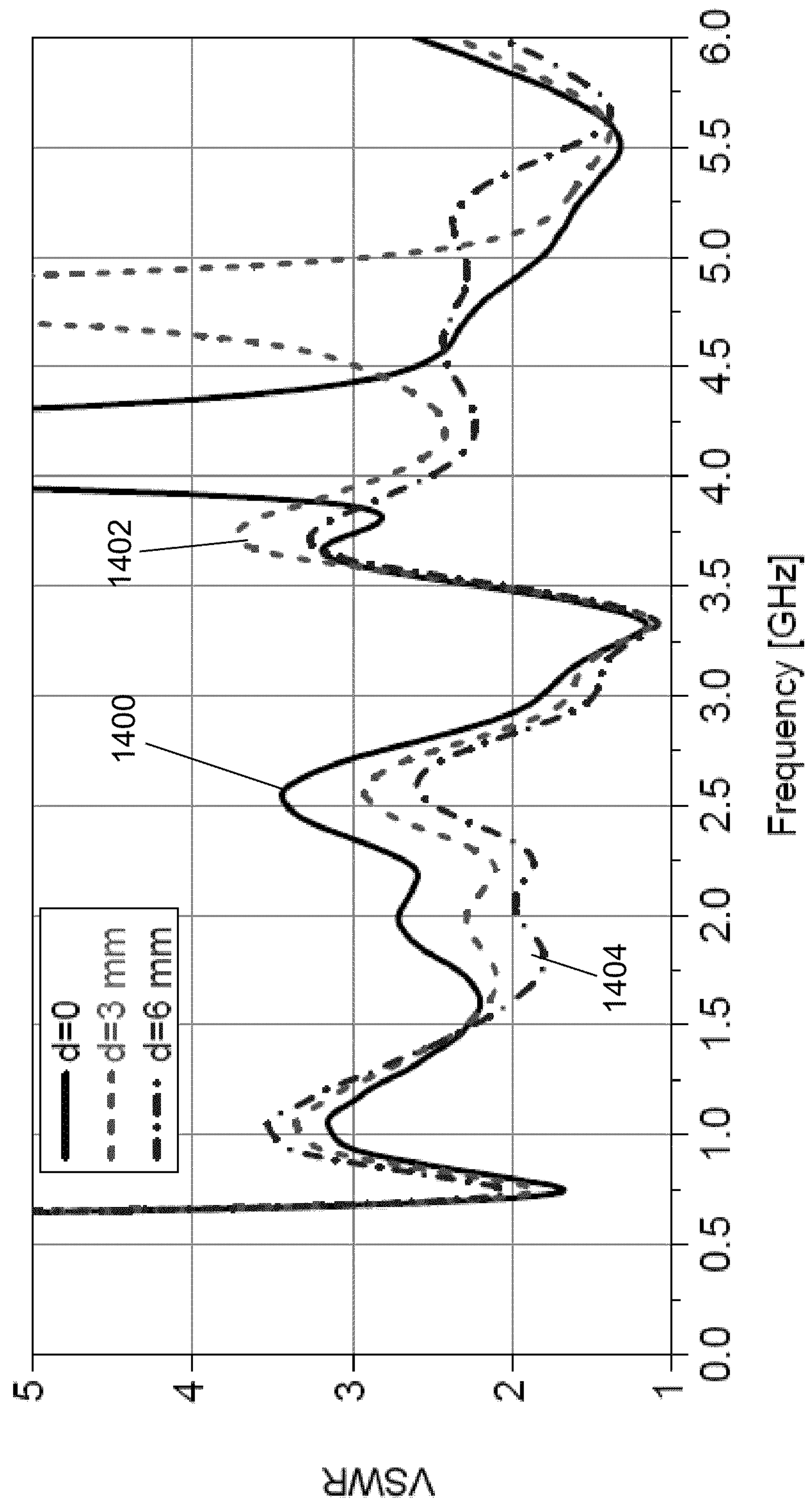


Fig. 13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d=6 mm
1400
1402
1404
VSWR
Frequency [GHz]
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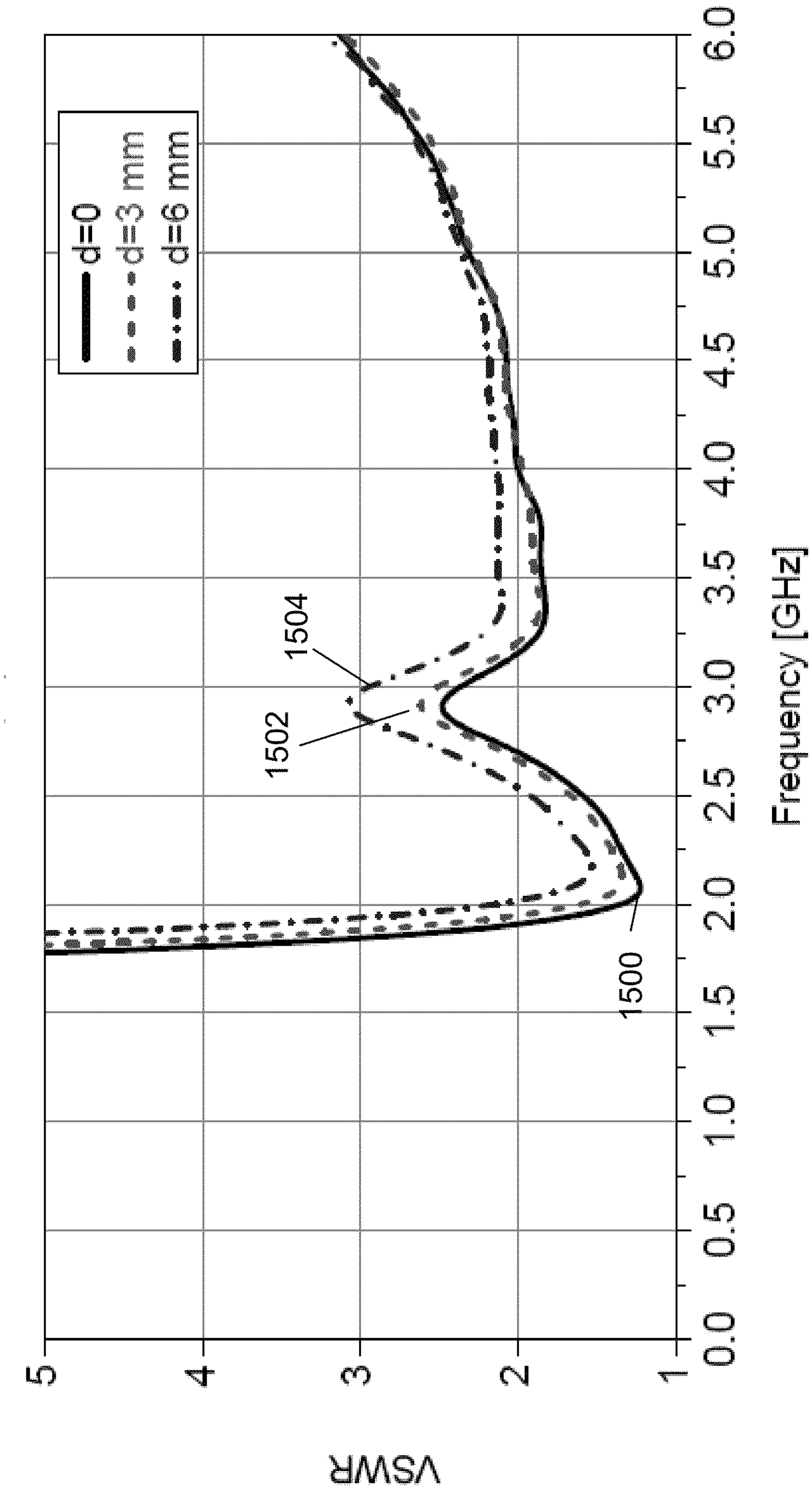
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
1
2
3
4
5

Fig. 14


VSWR
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3
2
1
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2.0
2.5
3.0
3.5
4.0
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5.0
5.5
6.0
d=0
d=3 mm
d=6 mm
1500
1502
1504

Fig. 15

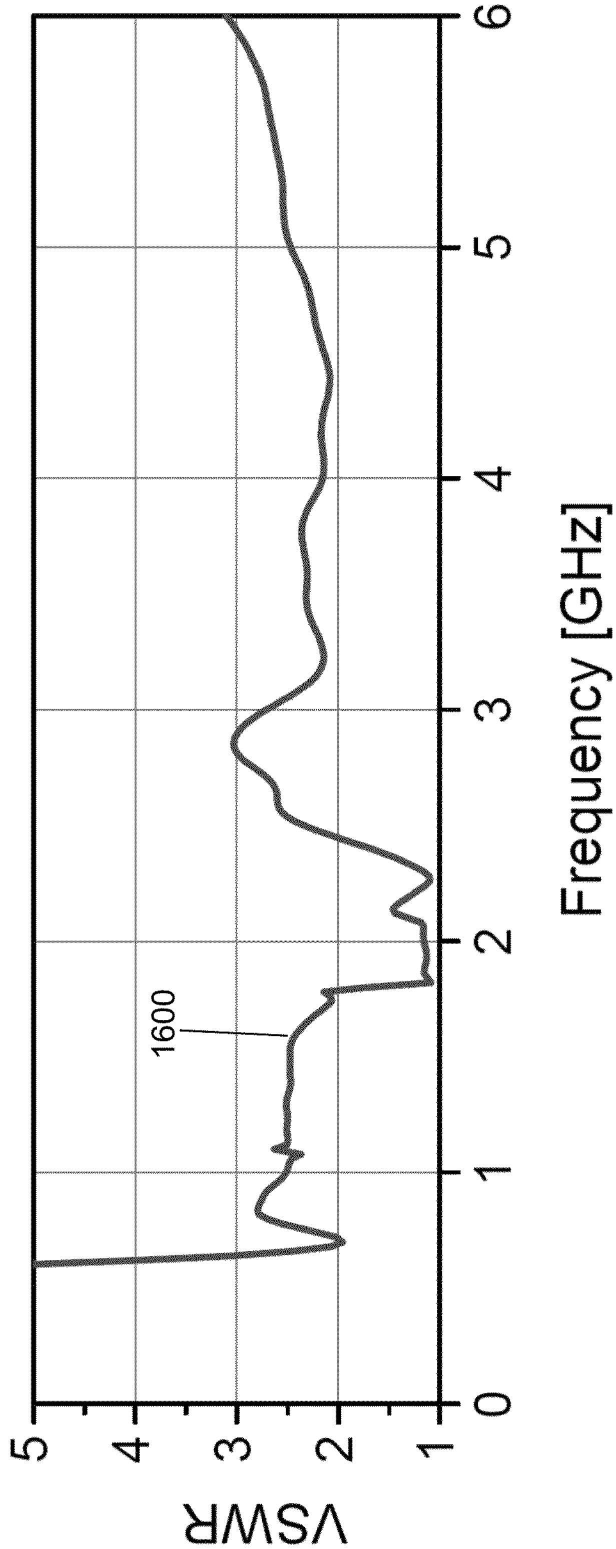
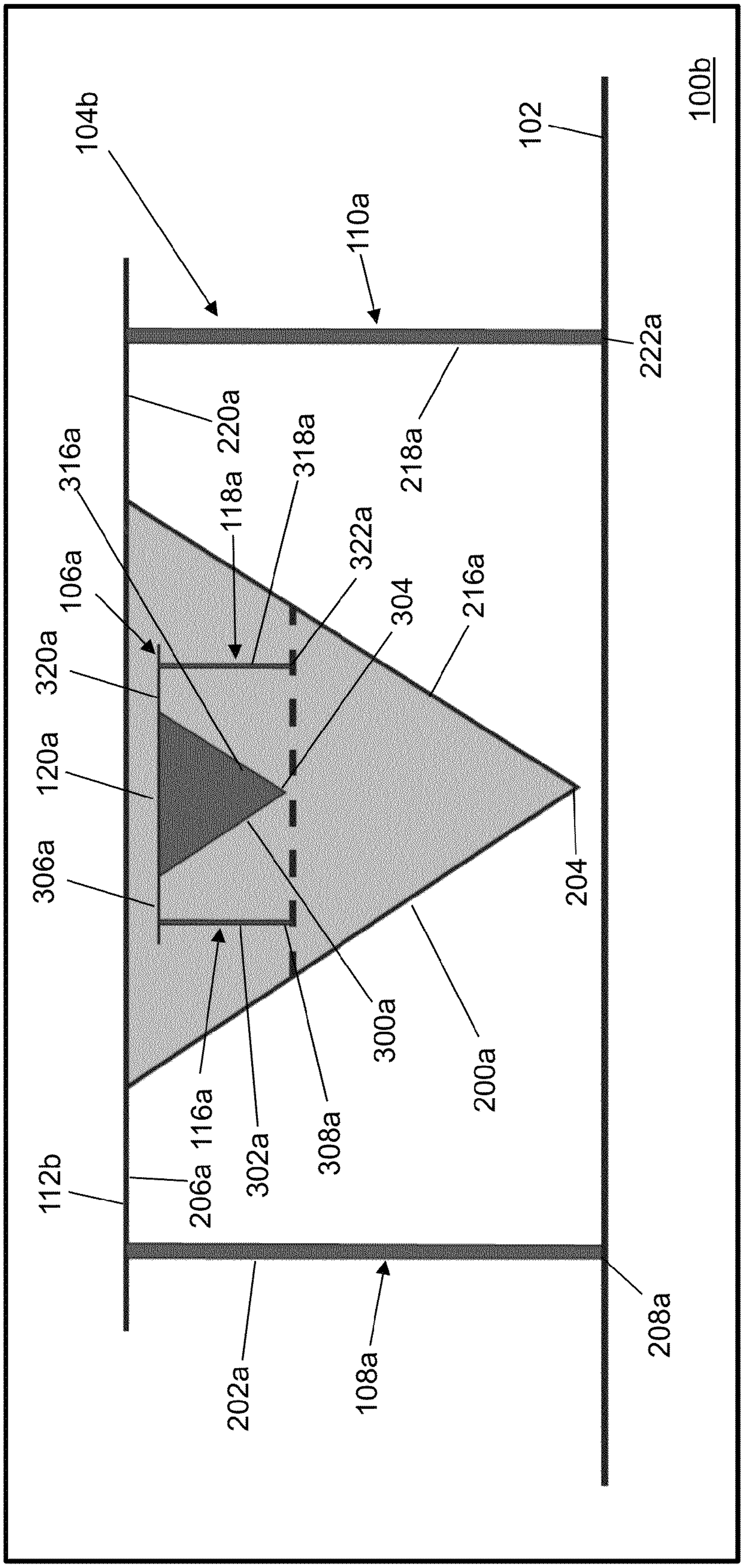


Fig. 16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200a
116a
302a
308a
112b
206a
202a
108a
208a

Fig. 17

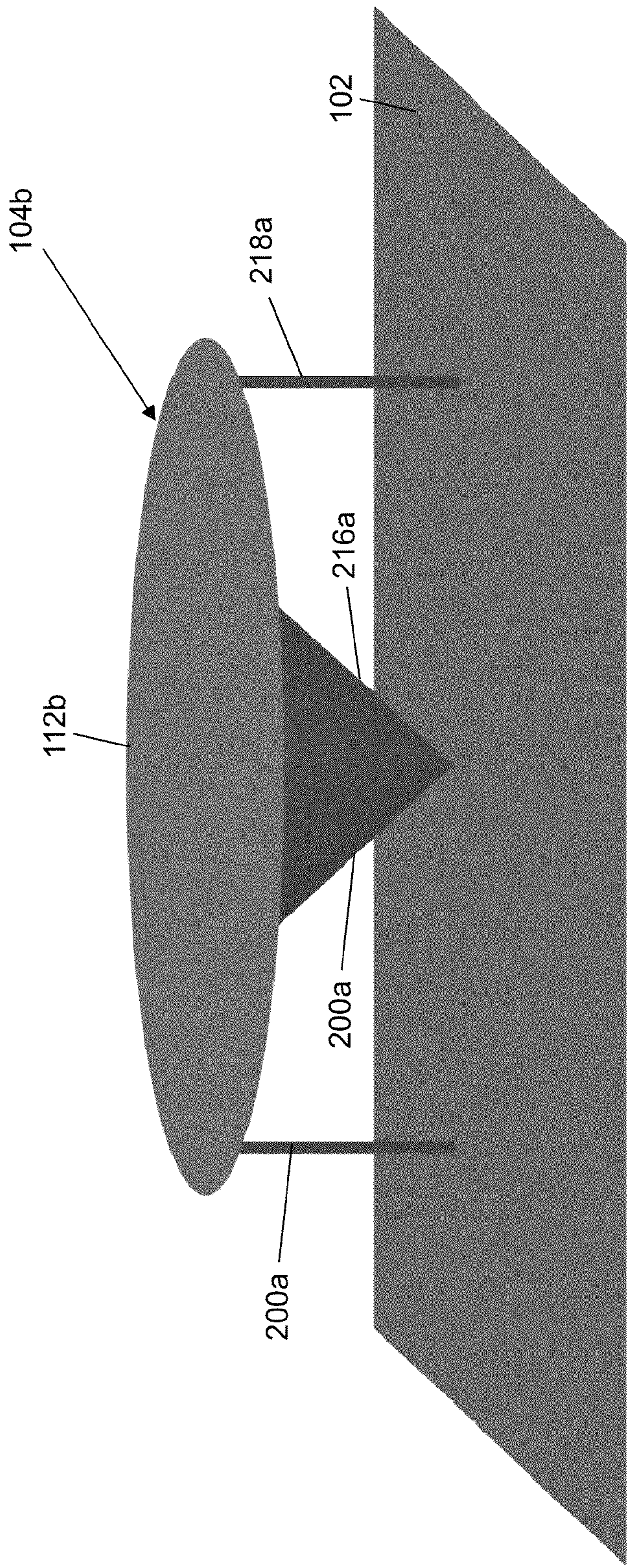

Fig. 18

ULTRA-WIDEBAND, LOW PROFILE ANTENNA

REFERENCE TO GOVERNMENT RIGHTS

This invention was made with government support under N00014-11-1-0618 awarded by the US Navy/ONR. The government has certain rights in the invention.

BACKGROUND

In some applications, ultra-wideband antennas are needed to operate at very low frequencies, for example, at or below the ultra high frequency band. At such frequencies, the electromagnetic wavelength is very large. Consequently, any antenna that is used at these frequencies is physically very large. This physically large dimension, i.e. 30-40 feet, may result in a very high antenna that can be easily seen.

An "electrically-small" antenna refers to an antenna or antenna element with relatively small geometrical dimensions compared to the wavelength of the electromagnetic fields the antenna radiates. Electrically-small antenna elements may be used in low frequency applications to overcome issues associated with the physical size of the antenna determined based on the wavelength.

SUMMARY

In an illustrative embodiment, an antenna system is provided. The antenna system includes, but is not limited to, a ground plane substrate, a first antenna, and a second antenna. The first antenna includes, but is not limited to, a first loop conductor, a second loop conductor, and a first conductor. The first loop conductor is electrically connected at a first point to a feed network and at a second point to the ground plane substrate. The second loop conductor is electrically connected at a third point to the feed network and at a fourth point to the ground plane substrate. The first conductor is mounted to and electrically connected to a first edge of the first loop conductor between the first point and the second point and to a second edge of the second loop conductor between the third point and the fourth point.

The second antenna includes, but is not limited to, a third loop conductor, a fourth loop conductor, and a second conductor. The third loop conductor is electrically connected at a fifth point to the feed network and at a sixth point to the first conductor. The fourth loop conductor is electrically connected at a seventh point to the feed network and at an eighth point to the first conductor. The second conductor is mounted to and electrically connected to a third edge of the third loop conductor between the fifth point and the sixth point and to a fourth edge of the fourth loop conductor between the seventh point and the eighth point.

Other principal features of the current disclosure 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 will be described referring to the accompanying drawings, wherein like numerals denote like elements.

FIG. **1** shows a perspective view of an antenna system in accordance with an illustrative embodiment.

FIG. **2** shows a side view of the antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **3** shows a side view of a top antenna of the antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **4** shows a perspective view of the top antenna of FIG. **3** in accordance with an illustrative embodiment.

FIG. **5** shows a perspective view of a pair of loop conductors of a bottom antenna of the antenna system of FIG. **1** in accordance with an illustrative embodiment.

FIG. **6** shows a perspective view of a second antenna system in accordance with an illustrative embodiment.

FIG. **7** shows a side view of the second antenna system of FIG. **6** in accordance with an illustrative embodiment.

FIG. **8** shows a perspective view of a conductor of a bottom antenna of the second antenna system of FIG. **6** in accordance with an illustrative embodiment.

FIG. **9** shows a block diagram of a feed network of the antenna systems of FIGS. **1** and **6** in accordance with an illustrative embodiment.

FIG. **10** is a graph showing an electric field distribution in an x-z plane of a bottom antenna of the antenna system of FIG. **1**.

FIG. **11** is a graph showing an electric field distribution in an y-z plane of a bottom antenna of the antenna system of FIG. **1**.

FIG. **12** is a graph showing a magnetic field distribution in an x-z plane of a bottom antenna of the antenna system of FIG. **1**.

FIG. **13** is a graph showing a magnetic field distribution in an y-z plane of a bottom antenna of the antenna system of FIG. **1**.

FIG. **14** is a graph showing a voltage standing wave ratio comparison between the bottom antennas of the antenna systems of FIGS. **1** and **6**.

FIG. **15** is a graph showing a voltage standing wave ratio comparison between the top antennas of the antenna systems of FIGS. **1** and **6**.

FIG. **16** is a graph showing a voltage standing wave ratio for the second antenna system of FIG. **6**.

FIG. **17** shows a side view of a third antenna system in accordance with an illustrative embodiment.

FIG. **18** shows a perspective view of a bottom antenna of the third antenna system of FIG. **17** with d=0 in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

With reference to FIG. **1**, a top perspective view of an antenna system **100** is shown in accordance with an illustrative embodiment. Antenna system **100** may include a ground plane substrate **102**, a first antenna **104**, and a second antenna **106**. Ground plane substrate **102** is electrically grounded and may be formed of any material suitable for forming an electrical ground for antenna system **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.

First antenna **104** may include a first loop conductor **108**, a second loop conductor **110**, and a first conductor **112**. First loop conductor **108** is electrically connected to a first feed connector **114** and to ground plane substrate **102**. First conductor **112** is mounted to and electrically connected to a first edge **206** (shown with reference to FIG. **2**) of first loop conductor **108** between first feed connector **114** and ground plane substrate **102**. Second loop conductor **110** is electrically connected to first feed connector **114** and to ground plane substrate **102**. First conductor **112** is mounted to and electrically connected to a second edge **220** (shown with reference to FIG.

2) of second loop conductor **110** between first feed connector **114** and ground plane substrate **102**. First loop conductor **108** is mounted to ground plane substrate **102** as a mirror image of second loop conductor **110**. As used herein, a loop conductor references a conductor that is electrically connected to receive an electrical signal at a feed point and to ground.

Second antenna may include a third loop conductor **116**, a fourth loop conductor **118**, and a second conductor **120**. Third loop conductor **116** is electrically connected to a second feed connector **122** and to first conductor **112**. Second conductor **120** is mounted to and electrically connected to a third edge **306** (shown with reference to FIG. **3**) of third loop conductor **116** between second feed connector **122** and first conductor **112**. Fourth loop conductor **118** is electrically connected to first feed connector **114** and to first conductor **112**. Second conductor **120** is mounted to and electrically connected to a fourth edge **320** (shown with reference to FIG. **3**) of fourth loop conductor **118** between second feed connector **122** and first conductor **112**. Third loop conductor **116** is mounted to first conductor **112** as a mirror image of fourth loop conductor **118**.

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, thermoform, rest on, rest against, 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.

With reference to FIG. **2**, a side view of antenna system **100** is shown in accordance with an illustrative embodiment. With reference to FIG. **5**, a perspective view of first loop conductor **108** and second loop conductor **110** is shown in accordance with an illustrative embodiment. Referring to FIGS. **2** and **5**, first loop conductor **108** and second loop conductor **110** are fed in parallel at a common feeding point, a first feed point **204**, that is electrically connected to first feed connector **114**. First loop conductor **108** may include a first loop inner conductor **200** and a first loop outer conductor **202**.

In the illustrative embodiment of FIGS. **2** and **5**, first loop conductor **108** has a quadrilateral shape, such as a kite or rhombus shape, when projected into a plane defined by ground plane substrate **102**. First loop inner conductor **200** forms a first isosceles triangle such that adjacent sides that extend from first feed point **204** are of equal length. First loop inner conductor **200** is electrically connected at first feed point **204** to first feed connector **114** that is connected to a feed network **900** (shown with reference to FIG. **9**). First loop inner conductor **200** is electrically connected along first edge **206**, an edge that is opposite first feed point **204**, to first conductor **112**.

First loop outer conductor **202** is electrically connected at a first short circuit connection **208** to ground plane substrate **102**. First loop outer conductor **202** forms a second isosceles triangle such that adjacent sides that extend from first short circuit connection **208** are of equal length. First loop outer conductor **202** is electrically connected along first edge **206**, an edge that is opposite first short circuit connection **208**, to first conductor **112**. First loop conductor **108** may be formed by bending a continuous sheet of material along a diagonal that forms first edge **206** between adjacent sides of the first and second isosceles triangles.

First loop inner conductor **200** has a first length **210** when projected into the plane defined by ground plane substrate **102**. First loop outer conductor **202** has a second length **212** when projected into the plane defined by ground plane substrate **102**. First length **210** and second length **212** may be equal indicating that first loop inner conductor **200** and first loop outer conductor **202** have the same size and that first loop conductor **108** forms a rhombus, instead of a kite, when projected into the plane defined by ground plane substrate **102**. First edge **206** extends above ground plane substrate **102** at a first height **214**.

Second loop conductor **110** may include a second loop inner conductor **216** and a second loop outer conductor **218**. In the illustrative embodiment of FIGS. **2** and **5**, second loop conductor **110** has a quadrilateral shape, such as a kite or rhombus shape, when projected into the plane defined by ground plane substrate **102**. Second loop inner conductor **216** forms a third isosceles triangle such that adjacent sides that extend from first feed point **204** are of equal length. Second loop inner conductor **216** is electrically connected at first feed point **204** to first feed connector **114** that is connected to feed network **900**. Second loop inner conductor **216** is electrically connected along second edge **220**, an edge that is opposite first feed point **204**, to first conductor **112**.

Second loop outer conductor **218** is electrically connected at a second short circuit connection **222** to ground plane substrate **102**. Second loop outer conductor **218** forms a fourth isosceles triangle such that adjacent sides that extend from second short circuit connection **222** are of equal length. Second loop outer conductor **218** is electrically connected along second edge **220**, an edge that is opposite second short circuit connection **222**, to first conductor **112**. Second loop conductor **110** may be formed by bending a continuous sheet of material along a diagonal that forms second edge **220** between adjacent sides of the third and fourth isosceles triangles.

In the illustrative embodiment, first conductor **112** has a first conductor width **124** (shown with reference to FIG. **1**). In the illustrative embodiment, first edge **206** and second edge **220** have a first edge width **500**. In the illustrative embodiment, first conductor width **124** is greater than first edge width **500**. First conductor **112** has a width of approximately twice first length **210** plus second length **212** to cover first loop conductor **108** and second loop conductor **110**.

In the illustrative embodiment, first antenna **104** includes two loops, first loop conductor **108** and second loop conductor **110**. In alternative embodiments, first antenna **104** may include one or more additional loops. In the illustrative embodiment, first loop conductor **108** and second loop conductor **110** are connected to ground plane substrate **102** at a single point, first short circuit connection **208** and second short circuit connection **222**, respectively. In alternative embodiments, first loop conductor **108** and second loop conductor **110** may be connected to ground plane substrate **102** at a plurality of points to form a plurality of short circuit connections. The short circuit connection point between the loop conductors and ground plane substrate **102** may vary in size and shape.

With reference to FIG. **3**, a side view of second antenna **106** mounted on first conductor **112** is shown in accordance with an illustrative embodiment. Third loop conductor **116** and fourth loop conductor **118** are fed in parallel at a common feeding point, a second feed point **304**, that is electrically connected to second feed connector **122**. Third loop conductor **116** may include a third loop inner conductor **300** and a third loop outer conductor **302**. In the illustrative embodiment of FIG. **3**, third loop conductor **116** has a quadrilateral shape, such as a kite or rhombus shape, when projected into the plane defined by ground plane substrate **102**. Third loop inner conductor **300** forms a fifth isosceles triangle such that adjacent sides that extend from second feed point **304** are of equal length. Third loop inner conductor **300** is electrically connected at second feed point **304** to second feed connector **122** that is connected to feed network **900**. Third loop inner conductor **300** is electrically connected along third edge **306**, an edge that is opposite second feed point **304**, to second conductor **120**.

Third loop outer conductor **302** is electrically connected at a third short circuit connection **308** to first conductor **112**. Third loop outer conductor **302** forms a sixth isosceles triangle such that adjacent sides that extend from third short circuit connection **308** are of equal length. Third loop outer conductor **302** is electrically connected along third edge **306**, an edge that is opposite third short circuit connection **308**, to second conductor **120**. Third loop conductor **116** may be formed by bending a continuous sheet of material along a diagonal that forms third edge **306** between adjacent sides of the fifth and sixth isosceles triangles.

Third loop inner conductor **300** has a third length **310** when projected into the plane defined by ground plane substrate **102**. Third loop outer conductor **302** has a fourth length **312** when projected into the plane defined by ground plane substrate **102**. Third length **310** and fourth length **312** may be equal indicating that third loop inner conductor **300** and third loop outer conductor **302** have the same size and that third loop conductor **116** forms a rhombus, instead of a kite, when projected into the plane defined by ground plane substrate **102**. In the illustrative embodiment of FIG. **3**, third length **310** is greater than fourth length **312**. Third edge **306** extends above first conductor **112** at a second height **314**.

Fourth loop conductor **118** may include a fourth loop inner conductor **316** and a fourth loop outer conductor **318**. In the illustrative embodiment of FIG. **3**, fourth loop conductor **118** has a quadrilateral shape, such as a kite or rhombus shape, when projected into the plane defined by ground plane substrate **102**. Fourth loop inner conductor **316** forms a seventh isosceles triangle such that adjacent sides that extend from second feed point **304** are of equal length. Fourth loop inner conductor **316** is electrically connected at second feed point **304** to second feed connector **122** that is connected to feed network **900**. Fourth loop inner conductor **316** is electrically connected along fourth edge **320**, an edge that is opposite second feed point **304**, to second conductor **120**.

Fourth loop outer conductor **318** is electrically connected at a fourth short circuit connection **322** to first conductor **112**. Fourth loop outer conductor **318** forms an eighth isosceles triangle such that adjacent sides that extend from fourth short circuit connection **322** are of equal length. Fourth loop outer conductor **318** is electrically connected along fourth edge **320**, an edge that is opposite fourth short circuit connection **322**, to second conductor **120**. Fourth loop conductor **118** may be formed by bending a continuous sheet of material along a diagonal that forms fourth edge **320** between adjacent sides of the seventh and eighth isosceles triangles.

With reference to FIG. **4**, a perspective view of second antenna **106** is shown in accordance with an illustrative embodiment. In the illustrative embodiment, second conductor **120** has a second conductor width **400**. First conductor **112** and second conductor **120** are generally flat and planar and oriented approximately parallel to the plane defined by ground plane substrate **102**. Third edge **306** and fourth edge **320** of third loop conductor **116** and of fourth loop conductor **118**, respectively, have a second edge width (not shown) that is smaller than second conductor width **400** in an illustrative embodiment.

In the illustrative embodiment, second antenna **106** includes two loops, third loop conductor **116** and fourth loop conductor **118**. In alternative embodiments, second antenna **106** may include one or more additional loops. In the illustrative embodiment, third loop conductor **116** and fourth loop conductor **118** are connected to ground plane substrate **102** at a single point, third short circuit connection **308** and fourth short circuit connection **322**, respectively. In alternative embodiments, third loop conductor **116** and fourth loop conductor **118** may be connected to first conductor **112** at a plurality of points to form a plurality of short circuit connections.

First antenna **104** and second antenna **106** may be formed of any conducting material(s) suitable for forming a radiator of antenna system **100**. For example, first antenna **104** and second antenna **106** may be formed of copper or brass sheets among many other options as understood by a person of skill in the art. First loop conductor **108**, second loop conductor **110**, first conductor **112**, third loop conductor **116**, fourth loop conductor **118**, and second conductor **120** may be formed of the same or different materials.

In an illustrative embodiment, second antenna **106** is a smaller scaled version of first antenna **104**. For example, second antenna **106** may be designed such that second antenna **106** has a lowest frequency of operation that approximately coincides with a highest frequency of operation of first antenna **104**. The highest frequency of operation of first antenna **104** may be determined by the maximum frequency at which a radiation pattern of first antenna **104** remains acceptable for the desired use of antenna system **100**. For example, the maximum frequency at which the radiation pattern of first antenna **104** remains approximately omni-directional may define the highest frequency of operation of first antenna **104**.

The lowest frequency of operation, f_{low}, for each antenna can be approximated based on the dimensions of first antenna **104** and/or of second antenna **106** using

$$f_{low}=\frac{l_1}{8\sqrt{l_1^2+h^2}\int_0^{l_1}\mu_0\varepsilon_0\left(\frac{xf+l_1W}{x(f-W)+Wl_1}\right)dx}$$

where l_1 is first length **210** or third length **310**, h is first height **214** or second height **314**, μ_0 is the magnetic permeability of free space, $\in_0$ is the permittivity of free space, x is an arbitrary variable for integration, f is first edge width **500** or the second edge width of third loop conductor **116** and of fourth loop conductor **118**, and W is first conductor width **124** or second conductor width **400**.

In the illustrative embodiment of FIGS. **1-4**, first conductor **112** and second conductor **120** are generally flat and have a square or rectangular shape. In alternative embodiments, first conductor **112** and second conductor **120** may form other polygonal, circular, or elliptical shapes and may not be flat. In the illustrative embodiment of FIGS. **1-5**, first loop conductor **108**, second loop conductor **110**, third loop conductor **116**, and fourth loop conductor **118** form a kite or rhombus shape when projected into ground plane substrate **102**. In alternative embodiments, first loop conductor **108**, second loop conductor **110**, third loop conductor **116**, and fourth loop conductor **118** may form other polygonal, circular, or elliptical shapes when projected into ground plane substrate **102**.

For illustration, first feed connector **114** of first antenna **104** may be a subminiature version A (SMA) connector mounted at a center of ground plane substrate **102**. Second antenna **106** may be fed with a semi-rigid coaxial cable that passes through a hole drilled in ground plane substrate **102**. The hole may be positioned off center with respect to first feed connector **114** to avoid first feed connector **114**. Above ground plane substrate **102**, an S-shaped bend may be formed in the semi-rigid coaxial cable to feed second antenna **106** at a center of first conductor **112**. An outer conductor of the semi-rigid coaxial cable may be connected to first conductor **112** of first antenna **104**. A center conductor of the semi-rigid coaxial cable may be connected to second feed connector **122**. An outer shield of the semi-rigid coaxial cable may be electrically connected to ground plane substrate **102** where the semi-rigid coaxial cable passes through ground plane substrate **102** to ensure that any current induced on the outer shield by first antenna **104** is shorted to ground and does not flow along the semi-rigid coaxial cable to excite second antenna **106**.

With reference to FIG. **6**, a top perspective view of a second antenna system **100***a* is shown in accordance with an illustrative embodiment. Second antenna system **100***a* may include ground plane substrate **102**, a third antenna **104***a*, and second antenna **106**. Third antenna **104***a* may include first loop conductor **108**, second loop conductor **110**, and a third conductor **112***a*. Third conductor **112***a* is mounted to and electrically connected to first edge **206** of first loop conductor **108** between first feed connector **114** and ground plane substrate **102**. Third conductor **112***a* is mounted to and electrically connected to second edge **220** of second loop conductor **110** between first feed connector **114** and ground plane substrate **102**.

Third conductor **112***a* forms a recess formed between first loop inner conductor **200** and second loop inner conductor **216** within which second antenna **106** is mounted to reduce an overall height of second antenna system **100***a* relative to antenna system **100**. With reference to FIG. **7**, a side view of second antenna system **100***a* is shown in accordance with an illustrative embodiment. Second antenna system **100***a* is reduced in overall height relative to an overall height of antenna system **100**. The overall height of antenna system **100** is equal to first height **214** plus second height **314**. The overall height of second antenna system **100***a* is reduced relative to antenna system **100** by a recess depth **700**. As a result, second antenna **106** extends above first edge **206** a distance of second height **314** minus recess depth **700**. Due to this, a minimum distance between third short circuit connection **308** and ground plane substrate **102** is less than a minimum distance between first edge **206** and ground plane substrate **102**.

With reference to FIG. **8**, a perspective view of third conductor **112***a* is shown in accordance with an illustrative embodiment though other conductor structures may be used. Third conductor **112***a* may include a first plate **804**, a second plate **806**, and a third plate **808** that are generally planar and flat and extend approximately parallel to ground plane substrate **102**. First plate **804**, second plate **806**, and third plate **808** each have a width equal to first conductor width **124**. Third conductor **112***a* has a total length **802**. The cavity formed between first edge **206** and second edge **220** has a cavity length **818** within which second antenna **106** is mounted.

A right edge **820** of first plate **804** mounts to first edge **206**. A left edge **824** of third plate **808** mounts to second edge **220**. A first sloped wall **810** extends from right edge **820** of first plate **804** to a left edge **822** of second plate **806**. A second sloped wall **812** extends from left edge **824** of third plate **808** to a right edge **826** of second plate **806**. First sloped wall **810** mounts to and extends parallel to first loop inner conductor **200**. Second sloped wall **812** mounts to and extends parallel to second loop inner conductor **216**. A third sloped wall **814** extends upward from a top edge of second plate **806**. A fourth sloped wall **816** extends upward from a bottom edge of second plate **806**. First sloped wall **810**, second sloped wall **812**, third sloped wall **814**, and fourth sloped wall **816** form the recess within which second antenna **106** is mounted. Third short circuit connection **308** and fourth short circuit connection **322** are mounted to second plate **806** of third conductor **112***a*. Second feed connector **122** is mounted to second plate **806** of third conductor **112***a*.

Third antenna **104***a* may be formed of any conducting material(s) suitable for forming a radiator of second antenna system **100***a*. For example, third antenna **104***a* may be formed of copper or brass sheets among many other options as understood by a person of skill in the art. Third conductor **112***a* may be formed of the same or different materials.

With reference to FIG. **9**, a block diagram of feed network **900** is shown in accordance with an illustrative embodiment. To work as a single, ultra-wideband radiator, antenna system **100** or second antenna system **100***a* uses a frequency-dependent feed network that feeds the appropriate antenna based on a transmission frequency of an input signal input on a feed line **912**. Feed network **900** may include a diplexer **902** configured to provide a first signal having a transmission frequency below approximately a first frequency to first feed connector **114** of first antenna **104** and to provide a second signal having a transmission frequency approximately above the first frequency to second feed connector **122** of second antenna **106**. Second antenna **106** is a smaller scaled version of first antenna **104** based on the first frequency. In an illustrative embodiment, diplexer **902** may include a low pass filter **904** and a high pass filter **906** designed based on the first frequency as understood by a person of skill in the art. Feed network **900** may further include an impedance matching circuit **908** electrically connected to diplexer **902**.

A sharp out-of-band rejection for diplexer **902** may be provided using high-order filters (i.e., 6^{th} order) for low pass filter **904** and for high pass filter **906** to ensure that each antenna is excited in the desired frequency band of operation. Having a sharp out-of-band rejection is particularly important in the case of low pass filter **904** used to feed first antenna **104**/third antenna **104***a* because first antenna **104**/third antenna **104***a* can operate at higher frequency bands and its excitation may result in deterioration of the radiation patterns of antenna system **100** or second antenna system **100***a*, respectively. Second feed connector **122** may be a coaxial cable connector with coaxial cable passing through ground plane substrate **102** of first conductor **112** or third conductor **112***a*. Since the coaxial cable passes through the near-field of first antenna **104**/third antenna **104***a*, it may slightly impact the impedance matching of first antenna **104**/third antenna **104***a*. As a result, in the illustrative embodiment, impedance matching circuit **908** includes a series connected capacitor **910** connected between low pass filter **904** and first feed connector **114** of first antenna **104**/third antenna **104***a*. Series connected capacitor **910** is selected to improve an overall voltage standing wave ratio (VSWR) of antenna system **100** or of second antenna system **100***a*.

For illustration, first antenna **104** (or third antenna **104***a*) may lose its omnidirectionality at ~2 gigahertz (GHz). Second antenna **106** may be designed to start radiating efficiently at ~2 GHz. Diplexer **902** then is designed to have a transition frequency for low pass filter **904** and high pass filter **906** at ~2 GHz.

With reference to FIG. **10**, a normalized electric field distribution from first antenna **104** in an x-z (see axes in FIG. **1**) plane at 1.0 GHz is shown. With reference to FIG. **11**, a normalized electric field distribution from first antenna **104** in a y-z plane at 1.0 GHz is shown. With reference to FIG. **12**, a normalized magnetic field distribution from first antenna **104** in the x-z plane at 1.0 GHz is shown. With reference to FIG. **13**, a normalized magnetic field distribution from first antenna **104** in the y-z plane at 1.0 GHz is shown. The intensities of the electric and magnetic fields in the central region of first antenna **104** (marked 'Field free') are significantly smaller (<~−25 dB) than the field intensities in the other regions. Thus, second antenna **106** is mounted in a relatively field free (<~−25 dB) area of first antenna **104**/third antenna **104***a*.

To examine the impact of recess depth **700** on the performance of second antenna system **100***a*, a prototype was simulated using the three-dimensional electromagnetic simulation CST Microwave Studio® developed by CST Computer Simulation Technology AG. The dimensions of first antenna **104**/third antenna **104***a* were 12.1 centimeters (cm)×12.1 cm×1.8 cm and of second antenna **106** were 4 cm×4 cm×0.9 cm. First length **210** and second length **212** were 30.2 cm. Third length **310** was 15.1 cm, and fourth length **312** was 4.5 cm. First edge width **500** of first loop conductor **108** and of second loop conductor **110** was 109 cm. The second edge width of third loop conductor **116** and of fourth loop conductor **118** was 36.3 cm. These dimensions were chosen so that first antenna **104**/third antenna **104***a* and second antenna **106** have lowest frequencies of operation of 0.6 GHz and 2 GHz, respectively. In the simulations, each antenna was fed with a lumped port at its feed location.

With reference to FIG. **14**, a VSWR of first antenna **104**/third antenna **104***a* for different values of recess depth **700**, d, are shown. A first VSWR curve **1400** shows the VSWR for first antenna **104** (d=0). A second VSWR curve **1402** shows the VSWR for third antenna **104***a* with d=3 millimeters (mm). A third VSWR curve **1404** shows the VSWR for third antenna **104***a* with d=6 mm. With reference to FIG. **15**, a VSWR of second antenna **106** for different values of d are shown. A fourth VSWR curve **1500** shows the VSWR for second antenna **106** with d=0. A fifth VSWR curve **1502** shows the VSWR for second antenna **106** with d=3 mm. A sixth VSWR curve **1504** shows the VSWR for second antenna **106** with d=6 mm.

As indicated in FIG. **14**, changing recess depth **700** impacts the VSWR of first antenna **104**/third antenna **104***a*. However, the most significant variations are observed at frequencies above 4 GHz, which fall outside the omni-directional bandwidth of first antenna **104**/third antenna **104***a*. The cavity depth does not significantly impact the VSWR of first antenna **104**/third antenna **104***a* below 4 GHz for d as large as 6 mm. As indicated in FIG. **15**, increasing d slightly deteriorates the VSWR of second antenna **106**, particularly in the frequency band of 2.5-3 GHz. Based on the results shown in FIGS. **14** and **15**, choosing a cavity depth of d=6 mm offers a compromise between the overall height and impedance matching of second antenna system **100***a*.

To predict the response of second antenna system **100***a* with feed network **900**, second antenna system **100***a* was simulated in CST Microwave Studio® including the coaxial cable for feeding second antenna **106**. With reference to FIG. **16**, a simulated input VSWR curve **1600** of second antenna system **100***a* is shown as seen on feed line **912** of feed network **900**. The response of third antenna **104***a* and second antenna **106** with d=6 mm can be combined successfully and is expected to have a VSWR below 3 from 0.64 to 6 GHz. Second antenna system **100***a* further has electrical dimensions of $0.24\lambda_{min}\times0.24\lambda_{min}\times0.04\lambda_{min}$, where λ_{min} is a wavelength at a lowest operational frequency of second antenna system **100***a*.

With reference to FIG. **17**, a side view of a third antenna system **100***b* is shown in accordance with an illustrative embodiment. Third antenna system **100***b* may include ground plane substrate **102**, a fourth antenna **104***b*, and a fifth antenna **106***a*. With reference to FIG. **18**, a top perspective view of fourth antenna **104***b* with d=0 mounted on ground plane substrate **102** is shown in accordance with an illustrative embodiment.

Fourth antenna **104***b* may include a fifth loop conductor **108***a*, a sixth loop conductor **110***a*, and a fourth conductor **112***b*. Fifth loop conductor **108***a* is electrically connected to first feed point **204** and to ground plane substrate **102** at a sixth short circuit connection **208***a*. Fifth loop conductor **108***a* may include a first semi-circular conductor **200***a* and a first rod shaped conductor **202***a*. First semi-circular conductor **200***a* is electrically connected between first feed point **204** and fourth conductor **112***b*. First rod shaped conductor **202***a* is electrically connected between sixth short circuit connection **208***a* and fourth conductor **112***b*. A fifth edge **206***a* extends around a semi-circular edge of first semi-circular conductor **200***a* along fourth conductor **112***b* to a top edge of first rod shaped conductor **202***a* to provide the loop to ground.

Sixth loop conductor **110***a* is electrically connected to first feed point **204** and to ground plane substrate **102** at a seventh short circuit connection **222***a*. Sixth loop conductor **110***a* may include a second semi-circular conductor **216***a* and a second rod shaped conductor **218***a*. Second semi-circular conductor **216***a* is electrically connected between first feed point **204** and fourth conductor **112***b*. Second rod shaped conductor **218***a* is electrically connected between seventh short circuit connection **222***a* and fourth conductor **112***b*. A sixth edge **220***a* extends around a semi-circular edge of second semi-circular conductor **216***a* along fourth conductor **112***b* to a top edge of second rod shaped conductor **218***a* to provide the loop to ground. Fifth loop conductor **108***a* is mounted to ground plane substrate **102** as a mirror image of sixth loop conductor **110***a*.

Fifth antenna **106***a* may include a seventh loop conductor **116***a*, an eighth loop conductor **118***a*, and a fifth conductor **120***a*. Seventh loop conductor **116***a* is electrically connected to second feed point **304** and to fourth conductor **112***b* at an eighth short circuit connection **308***a*. Seventh loop conductor **116***a* may include a third semi-circular conductor **300***a* and a third rod shaped conductor **302***a*. Third semi-circular conductor **300***a* is electrically connected between second feed point **304** and fifth conductor **120***a*. Third rod shaped conductor **302***a* is electrically connected between eighth short circuit connection **308***a* and fifth conductor **120***a*. A seventh edge **306***a* extends around a semi-circular edge of third semi-circular conductor **300***a* along fifth conductor **120***a* to a top edge of third rod shaped conductor **302***a* to provide the loop to ground.

Eighth loop conductor **118***a* is electrically connected to second feed point **304** and to fourth conductor **112***b* at a ninth short circuit connection **322***a*. Eighth loop conductor **118***a* may include a fourth semi-circular conductor **316***a* and a fourth rod shaped conductor **318***a*. Fourth semi-circular conductor **316***a* is electrically connected between second feed point **304** and fifth conductor **120***a*. Fourth rod shaped conductor **318***a* is electrically connected between ninth short circuit connection **322***a* and fifth conductor **120***a*. An eighth edge **320***a* extends around a semi-circular edge of fourth semi-circular conductor **316***a* along fifth conductor **120***a* to a top edge of fourth rod shaped conductor **318***a* to provide the loop to ground. Seventh loop conductor **116***a* is mounted to fifth conductor **120***a* as a mirror image of eighth loop conductor **118***a*.

In the illustrative embodiment of FIGS. **17** and **18**, first semi-circular conductor **200***a*, second semi-circular conductor **216***a*, third semi-circular conductor **300***a*, and fourth semi-circular conductor **316***a* form a cone, and fifth conductor **120***a* has a circular shape when projected into the plane defined by ground plane substrate **102**. Other shapes may be used.

First rod shaped conductor **202***a* and second rod shaped conductor **218***a* form a right angle at the connection point with ground plane substrate **102** though first rod shaped conductor **202***a* and second rod shaped conductor **218***a* may be positioned closer to or further from first feed point **204** to form an angle that is less than ±90°. Third rod shaped conductor **302***a* and fourth rod shaped conductor **318***a* form a right angle at the connection point with fourth conductor **112***b* though third rod shaped conductor **302***a* and fourth rod shaped conductor **318***a* may be positioned closer to or further from second feed point **304** to form an angle that is less than ±90°. First rod shaped conductor **202***a*, second rod shaped conductor **218***a*, third rod shaped conductor **302***a*, and fourth rod shaped conductor **318***a* further may have other cross sectional shapes such as elliptical or polygonal. First rod shaped conductor **202***a* and second rod shaped conductor **218***a* further may be mounted to fourth conductor **112***b* closer to of further from first semi-circular conductor **200***a* and second semi-circular conductor **216***a*, respectively. Third rod shaped conductor **302***a* and fourth rod shaped conductor **318***a* further may be mounted to fifth conductor **120***a* closer to or further from third semi-circular conductor **300***a* and fourth semi-circular conductor **316***a*, respectively.

Though not shown in FIGS. **17** and **18**, first feed point **204** and second feed point **304** connect to first feed connector **114** and second feed connector **122**, respectively, as discussed with reference to antenna system **100**. First feed connector **114** and second feed connector **122** of third antenna system **100***b* may be connected to feed network **900**.

Fourth antenna **104***b* and fifth antenna **106***a* may be formed of any conducting material(s) suitable for forming a radiator of third antenna system **100***b*. For example, fourth antenna **104***b* and fifth antenna **106***a* may be formed of copper or brass sheets among many other options as understood by a person of skill in the art. Fifth loop conductor **108***a*, sixth loop conductor **110***a*, fourth conductor **112***b*, seventh loop conductor **116***a*, eighth loop conductor **118***a*, and fifth conductor **120***a* may be formed of the same or different materials.

The word "illustrative" is used herein to mean serving as an illustrative, 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, for the purposes of the description, the use of "and" or "or" is intended to include "and/or" unless specifically indicated to only include "and" or "or". Use of directional terms, such as top, bottom, right, left, front, back, upper, lower, above, below, etc. are merely intended to facilitate reference to the various surfaces of the described structures relative to the orientations shown in the drawings and are not intended to be limiting in any manner.

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. An antenna system comprising:
- a ground plane substrate that is generally flat;
- a first antenna comprising
  - a first loop conductor electrically connected at a first point to a feed network and at a second point to the ground plane substrate;
  - a second loop conductor electrically connected at a third point to the feed network and at a fourth point to the ground plane substrate; and
  - a first conductor mounted to and electrically connected to a first edge of the first loop conductor between the first point and the second point and to a second edge of the second loop conductor between the third point and the fourth point; and
- a second antenna comprising
  - a third loop conductor electrically connected at a fifth point to the feed network and at a sixth point to the first conductor;
  - a fourth loop conductor electrically connected at a seventh point to the feed network and at an eighth point to the first conductor; and
  - a second conductor mounted to and electrically connected to a third edge of the third loop conductor between the fifth point and the sixth point and to a fourth edge of the fourth loop conductor between the seventh point and the eighth point.

2. The antenna system of claim **1**, wherein the second conductor is generally flat and oriented in a first plane approximately parallel to a second plane defined by the ground plane substrate.

3. The antenna system of claim **2**, wherein the first conductor is generally flat and oriented in a third plane approximately parallel to the first plane and to the second plane.

4. The antenna system of claim **2**, wherein the second conductor has a polygonal shape when projected into the second plane.

5. The antenna system of claim **2**, wherein the first conductor is generally flat and oriented in a third plane approximately parallel to the first plane and to the second plane except for a recess formed by a first wall that extends from the first edge downward toward the first point and a second wall that extends from the second edge downward toward the third point.

6. The antenna system of claim **1**, further comprising the feed network, wherein the feed network comprises a diplexer configured to provide a first signal having a transmission frequency below approximately a first frequency to the first antenna and to provide a second signal having a transmission frequency approximately above the first frequency to the second antenna.

7. The antenna system of claim **6**, wherein the feed network further comprises an impedance matching circuit electrically connected to the diplexer.

8. The antenna system of claim **7**, wherein the impedance matching circuit comprises a series connected capacitor connected between the diplexer and the first antenna.

9. The antenna system of claim **6**, wherein the second antenna is a smaller scaled version of the first antenna, wherein the second antenna is scaled in size relative to the first antenna based on the first frequency.

10. The antenna system of claim **1**, further comprising a third antenna comprising:

a fifth loop conductor electrically connected at a ninth point to the feed network and at a tenth point to the second conductor;

a sixth loop conductor electrically connected at an eleventh point to the feed network and at a twelfth point to the second conductor; and

a third conductor mounted to and electrically connected to a fifth edge of the fifth loop conductor between the ninth point and the tenth point and to a sixth edge of the sixth loop conductor between the eleventh point and the twelfth point.

11. The antenna system of claim **1**, wherein the first antenna further comprises a fifth loop conductor electrically connected at a ninth point to the feed network, at a tenth point to the ground plane substrate, and along a fifth edge to the first conductor.

12. The antenna system of claim **1**, wherein the sixth point and the eighth point are between the first edge and the second edge.

13. The antenna system of claim **12**, wherein a minimum distance between the sixth point and the ground plane substrate is less than a minimum distance between the first edge and the ground plane substrate.

14. The antenna system of claim **12**, wherein the first conductor extends from the first edge generally parallel to the ground plane substrate away from the second antenna, wherein the first conductor extends from the second edge generally parallel to the ground plane substrate away from the second antenna, wherein the first conductor extends from the first edge downward toward the first point and along the first loop conductor to define a fifth edge, wherein the first conductor extends from the second edge downward toward the third point and along the second loop conductor to define a sixth edge, and wherein the first conductor extends generally parallel to the ground plane substrate between the fifth edge and the sixth edge.

15. The antenna system of claim **1**, wherein the first point and the third point are between the first edge and the second edge.

16. The antenna system of claim **1**, wherein the second loop conductor is mounted as a mirror image of the first loop conductor.

17. The antenna system of claim **16**, wherein the first loop conductor has a quadrilateral shape when projected into a plane defined by the ground plane substrate, wherein a first pair of adjacent sides of the quadrilateral shape that extend from the first point are of equal length and a second pair of adjacent sides of the quadrilateral shape that extend from the second point are of equal length.

18. The antenna system of claim **17**, wherein the first edge extends along a diagonal that connects the first pair of adjacent sides and the second pair of adjacent sides.

19. The antenna system of claim **16**, wherein the first loop conductor is connected to the ground plane substrate at only the second point.

20. The antenna system of claim **16**, wherein the first loop conductor comprises a half-cone conductor and a rod conductor, wherein the half-cone conductor is electrically connected at the first point to the feed network and at a ninth point to the first conductor, wherein the rod conductor is electrically connected at the second point to the ground plane substrate and at a tenth point to the first conductor.

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