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(54) Title: FRACTAL-RECTANGULAR REACTIVE IMPEDANCE SURFACE FOR ANTENNA MINIATURIZATION

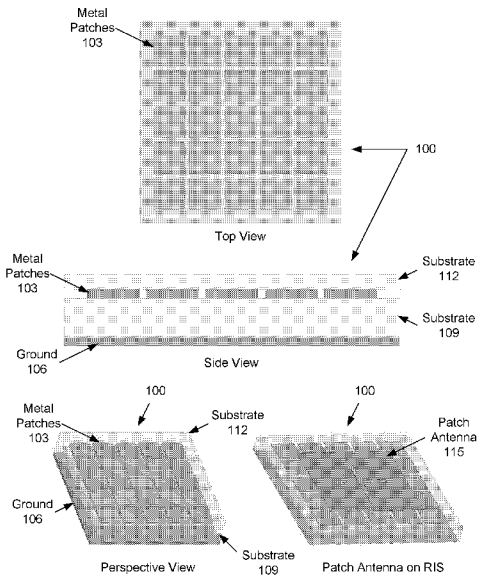


FIG. 1

(57) Abstract: Various examples are provided that are related to fractal-based reactive impedance surfaces. These surfaces allow for miniaturization of antennas. In one example, a fractal rectangular reactive impedance surface (FR-RIS) includes a plurality of fractal rectangular (FR) patches having an outer edge defined by a fractal rectangular pattern that is repeated along each side of inner FR patches of the plurality of FR patches. The fractal rectangular pattern of a FR patch matches with the fractal rectangular pattern of an adjacent FR patch. An antenna can include a planar antenna disposed over the FR-RIS.

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— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

FRACTAL-RECTANGULAR REACTIVE IMPEDANCE SURFACE FOR ANTENNA MINIATURIZATION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to, and the benefit of, co-pending U.S. provisional application entitled "Fractal-Rectangular Reactive Impedance Surface for Antenna Miniturization" having serial no. 62/322,448, filed April 14, 2016, which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under agreement 120957 awarded by the Multi-Functional Integrated System Technology (MIST) Center of the National Science Foundation (NSF). The Government has certain rights to the invention.

BACKGROUND

[0003] Planar antennas, because of their ease of fabrication and integration as well as compactness and low-profile characteristics, are highly desirable for wireless communication systems. The substrates of planar antennas play a very important role in achieving desirable electrical and physical characteristics. Design of antenna elements with significant front-to-back radiation ratio is either accomplished through the use of metal-backed substrates or high dielectric superstrates. Use of a reactive impedance surface (RIS) as a substrate for planar antennas can enhance the bandwidth and radiation characteristics of the antenna.

SUMMARY

[0004] Aspects of the present disclosure are related to fractal-based reactive impedance surfaces for use with antennas.

[0005] In one aspect, among others, a fractal rectangular reactive impedance surface (FR-RIS) comprises a plurality of fractal rectangular (FR) patches having an outer edge defined by a fractal rectangular pattern that is repeated along each side of inner FR patches of the plurality of FR patches, where the fractal rectangular pattern of one of the plurality of FR patches matches with the fractal rectangular pattern of an adjacent FR patch of the plurality of FR patches. In one or more aspects, an antenna can comprise a planar antenna disposed over the FR-RIS. The fractal rectangular pattern can comprise a rectangular tab extending outward from each side of the inner FR patches and a corresponding rectangular recess extending inward from each side of the inner FR patches. The FR-RIS can comprise a gap defined by the fractal rectangular pattern of adjacent FR patches of the plurality of FR patches, wherein the gap distance between the adjacent FR patches substantially constant. A capacitance of the FR-RIS can be based at least in part upon a length of the outer edge of the plurality of FR patches.

[0006] In one or more aspects, the FR-RIS can comprise a substrate disposed between the planar antenna and the plurality of FR patches. The planar antenna can be coupled to a feeding line that passes through the plurality of FR patches and the substrate. The feeding line can be a coaxial feeding line. The plurality of FR patches can be disposed on a first side of a substrate, and the FR-RIS comprises a ground plane disposed on a second side of the substrate opposite the plurality of FR patches. An inductance of the FR-RIS can be based at least in part upon a distance between the ground plane and the plurality of FR patches. The inductance of the FR-RIS can be further based upon a shape of the FR patches.

[0007] In one or more aspects, the planar antenna is a patch antenna. The patch antenna can comprise a slot. The slot can be rotated with respect to the patch antenna. The slot can be rotated at an angle of 45 degrees with respect to edges of the plurality of FR patches. In one or more aspects, an outer edge of the FR-RIS defines a rectangular shape. The rectangular shape can be a square. Outer FR patches of the plurality of FR patches can be distributed along the outer edge of the FR-RIS, the outer FR patches trimmed to provide the rectangular shape. In one or more aspects, the patch antenna disposed over the

FR-RIS can have a rectangular shape that is substantially aligned with the rectangular shape of the FR-RIS. The patch antenna can be smaller than the FR-RIS. The fractal rectangular pattern of adjacent FR patches of the plurality of FR patches are interdigitated.

[0008] Other systems, methods, features, and advantages of the present disclosure will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present disclosure, and be protected by the accompanying claims. In addition, all optional and preferred features and modifications of the described embodiments are usable in all aspects of the disclosure taught herein. Furthermore, the individual features of the dependent claims, as well as all optional and preferred features and modifications of the described embodiments are combinable and interchangeable with one another.

BRIEF DESCRIPTION OF THE DRAWINGS

[0001] Many aspects of the present disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0002] FIG. 1 illustrate an example of a conventional rectangular reactive impedance surface (CR-RIS) in accordance with various embodiments of the present disclosure.

[0003] FIGS. 2A and 2B illustrate examples of fractal rectangular reactive impedance surfaces (FR-RIS) in accordance with various embodiments of the present disclosure.

[0004] FIGS. 3A and 3B illustrate characteristics of a unit cell of CR-RIS and a unit cell of FR-RIS, respectively, in accordance with various embodiments of the present disclosure.

[0005] FIGS. 4A through 4E illustrate simulated characteristics of a patch antenna on a FR-RIS, in accordance with various embodiments of the present disclosure.

[0006] FIG. 5 is an example of a GPS patch antenna on a FR-RIS, in accordance with various embodiments of the present disclosure.

[0007] FIGS. 6A through 6D illustrate simulated characteristics of the GPS antenna of FIG. 5, in accordance with various embodiments of the present disclosure.

[0008] FIGS. 7A through 7D are images illustrating the fabrication of the GPS antenna of FIG. 5, in accordance with various embodiments of the present disclosure.

[0009] FIG 7E includes images showing an antenna characterization setup.

[0010] FIGS. 8A through 8D compare measured and simulated characteristics of the GPS antenna of FIG. 5, in accordance with various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0011] Disclosed herein are various embodiments of methods related to fractal-based reactive impedance surfaces for use with antennas. Reference will now be made in detail to the description of the embodiments as illustrated in the drawings, wherein like reference numbers indicate like parts throughout the several views.

[0012] Referring to FIG. 1, shown are top, side and perspective views of a conventional rectangular reactive impedance surface (CR-RIS) 100 that includes a periodic pattern of square metallic patches 103 printed on a planar grounded substrate without any via. As shown in the side view, a ground plane 106 is disposed on one side of a first substrate 109. In the example of FIG. 1, a 5×5 pattern of patches 103 are disposed on the first substrate 109 opposite the ground 106. A second substrate 112 can be disposed over the patches 103.

[0013] The CR-RIS 100 has a purely reactive impedance (either inductive or capacitive). The gap between adjacent rectangular patches 103 produces capacitance and a ground plane 106 located at the bottom of the two substrates produces inductance of the CR-RIS 100, which determines the resonant frequency of the CR-RIS 100. In order to increase/decrease the resonant frequency and the surface impedance of the CR-RIS 100, the total length of the capacitive gap between the patches 103 should be changed by

increasing/decreasing the size of rectangular patch 103. The bigger size of the CR-RIS 100 is necessarily required for the lower resonant frequency of CR-RIS 100, which is undesirable for compact antenna applications.

[0014] Antenna miniaturization can be achieved by combining the inductive and/or capacitive behavior of the CR-RIS 100 with the capacitive and/or inductive behavior of the patch radiator 115 at relatively low frequencies, which can be lower than the resonant frequency. FIG. 1 illustrates an example of a patch antenna or radiator 115 on a CR-RIS 100. Additional discussion about the CR-RIS 100 is provided in "Antenna Miniaturization and Bandwidth Enhancement Using a Reactive Impedance Substrate" by Mosallaei *et al.* (*IEEE Trans. on Antennas and Propagation*, Vol. 52, No. 9, September 2004), which is hereby incorporated by reference in its entirety.

[0015] A fractal rectangular RIS (FR-RIS) can be utilized to reduce the antenna size and achieve compact high-gain antennas for high-efficiency wireless communication systems. The use of a FR-RIS allows the antenna size to be reduced by providing additional compensation for the capacitive impedance of the antenna. A wide variety of antennas can be integrated on top of the FR-RIS to achieve further antenna miniaturization, while maintaining the high gain and antenna efficiency. By scaling the fractal rectangular structure, the resonant frequency and surface impedance of the FR-RIS can be controlled.

[0016] Referring now to FIG. 2A, shown are top and side views of an example of an antenna on a fractal rectangular RIS (FR-RIS) 200 that includes a N×N periodic pattern of metallic patches 203 with fractal rectangular edges (or FR patches 203). The FR patches 203 include a fractal rectangular shape, one of which is highlighted by the dashed line in FIG. 2A, which can be scaled to adjust the total length of the capacitive gap between adjacent patches 203. By changing the length (or depth) and/or width of elements of the fractal pattern, the total length of the patches 203 can be increased or decreased without changing the total area of the patches 203. In addition, the length may be adjusted by changing the number of elements or steps of the fractal rectangular pattern. In the example of FIG. 2A, each side of the FR patch 203 includes a tab and corresponding recess. In other

embodiments, each side of the FR patch 203 can include a plurality of tabs and corresponding recesses, which may be grouped or interspersed along the side. In some embodiments, the fractal rectangular pattern can be repeated on the tab and in the recess. FIG. 2B shows examples of fractal rectangular patterns that can be implemented along the adjacent sides of the FR patches 203. As shown in FIG. 2A, the FR patches 203 along the outer edge of the FR-RIS 200 can be trimmed to provide a smooth rectangular shape for the FR-RIS 200.

[0017] As seen in the side view of FIG. 2A, the FR patches 203 are located between a first substrate 209 and a second substrate 212. In the example of FIG. 2A, a patch antenna 115 is on the side of the second substrate 212 opposite the FR patches 203. The first substrate 209 includes a metal ground plane 206 on the side opposite the FR patches 203. The gap between adjacent FR patches 203 and the gap between the pattern of FR patches 203 and the ground plane 206 produce capacitance (C). The length of each patch and the ground plane produces inductance (L). The FR-RIS 200 can be represented as a parallel LC tank circuit whose resonant frequency is inversely proportional to the square root of the product of the capacitance and inductance of FR-RIS 200. The FR-RIS 200 behaves as an inductive surface (or inductive impedance) below the resonant frequency and compensates for the capacitive impedance of the antennas, thereby realizing impedance matching and resulting in the antenna miniaturization. A size reduction of at least 20% (or more) can be achieved using a FR-RIS 200 instead of a CR-RIS 100 because of the higher inductive impedance produced by the fractal rectangular structure of the FR-RIS 200.

[0018] Referring next to FIGS. 3A and 3B, shown are characteristics of examples of a unit cell of a CR-RIS 100 of FIG. 1 and a unit cell of a FR-RIS 200 of FIG. 2A, respectively. Each unit cell being evaluated has an area of 5.4mm×5.4mm. In the example of FIG. 3A, the capacitance of the CR-RIS 100 can be controlled or adjusted by the distance of the gap 303 between the patches 103 and the inductance can be controlled or adjusted by the distance between the patches 103 and the ground plane (or perfect electrical conductor (PEC) surface) 106, and the shape of the patches. The distance between the patches 103

and the ground plane 106 can be defined by the thickness of the first substrate 109. As shown in FIG. 3A, the LC resonance occurs at 2.86 GHz. At a frequency of 2.45 GHz, the impedance of the unit cell of the CR-RIS 100 is 2.3+j377 Ohms.

[0019] A higher capacitance can be obtained in the same area by increasing the total length of the gap between adjacent FR-RIS patches 203. The fractal rectangular pattern can be adjusted to obtain a desired capacitance. In the example of FIG. 3B, the capacitance of the FR-RIS 200 can be controlled or adjusted by the distance of the gap 303 between the patches 203 and the inductance can be controlled or adjusted by the shape of the patches and by the distance between the patches 203 and the ground plane 206, which can be defined by the thickness of the first substrate 209. In the design of FIG. 2A, the LC resonance occurs at 2.5 GHz and the impedance of the unit cell of the FR-RIS 200, at the frequency of 2.45 GHz, is 96+j2065 Ohms.

[0020] The design of the 2.45 GHz antenna on a FR-RIS 200 of FIG. 2A with a patch antenna 115 with a slot rotated at 45 degrees was evaluated. The first substrate 209 between the FR patches 203 and the ground plane 209 comprised a thermoset microwave material (e.g., Rogers TMM® 6) with a thickness of 5.08mm, ε_r=6.2, and tanδ=0.002 and the second substrate 212 between the FR patches 203 and the patch antenna 115 comprised a thermoset microwave material (e.g., Rogers TMM® 3) with a thickness of 0.645mm, ε_r=3.45, and tanδ=0.002. The patch antenna 115 with the rotated slot was provided on the second substrate 212 to produce right-hand circular polarization (RHCP) gain. A coaxial feeding line 215 was passed through the ground plane 206, first substrate 209, FR patches 203, and second substrate 212 to provide a connection to the patch antenna 115. FIG. 4A is a plot of the simulated radiation pattern produced by the 2.45 GHz antenna on the FR-RIS 200 of FIG. 2A. As can be seen, the RHCP gain shows a broadside radiation pattern. FIG. 4B is a plot of the return loss and FIG. 4C is a plot of the axial ratio for the 2.45 GHz antenna design. The simulation results are summarized in the table of FIG. 4D. The 2.45 GHz rotated slot antenna on the FR-RIS 200 of FIG. 2A provides a 10dB bandwidth of 172 MHz and a 3dB axial ratio bandwidth of 46 MHz.

[0021] When compared to previous antenna designs on CR-RIS 100, the use of the FR-RIS offers improved characteristics with reduced antenna sizes. Referring to FIG. 4E, shown is a table comparing characteristics of (1) a mushroom structure as described in "Compact Circularly-Polarized Patch Antenna Loaded With Metamaterial Structures" by Dong *et al.* (*IEEE Trans. on Antennas and Propagation*, Vol. 59, No. 11, November 2011); (2) a 45 degree rotated slot as described in "Wideband Circularly Polarized Patch Antennas on Reactive Impedance Substrates" by Bernard *et al.* (*IEEE Antennas and Wireless Propagation Letters*, Vol. 10, September 2011); (3) a complementary split-ring resonator (CSRR) on a patch as described in "Miniaturized Patch Antennas loaded with Complementary Split-Ring Resonators and Reactive Impedance Surface" by Dong *et al.* (*European Conf. on Antennas and Propagation (EUCAP)*, April 2011); and (4) crossed slots on a patch as described in "RIS-Based Compact Circularly Polarized Microstrip Antennas" by Agarwal *et al.* (*IEEE Trans. on Antennas and Propagation*, Vol. 61, No. 2, February 2013). These four publications are hereby incorporated by reference in their entirety. As shown in FIG. 4E, use of the FR-RIS 200 allows for a 20% reduction in the size of the patch antenna 115 while providing an improved gain of 4.85 dBic.

[0022] A global positioning system (GPS) antenna on a FR-RIS was designed, evaluated, implemented and tested. FIG. 5 shows top and side views of the GPS antenna including a fractal rectangular RIS (FR-RIS) 300 that includes an N×N periodic pattern of FR patches 303. The FR patches 303 include a fractal rectangular shape, one of which is highlighted by the dashed line in FIG. 5, which can be scaled to adjust the total length of the capacitive gap between adjacent patches 303 as previously discussed. As can be seen, while the general shape of the FR patches 303 of FIG. 5 is similar to the FR patches 203 of FIG. 2A, the dimensions have been changed to accommodate the needs of the GPS design.

[0023] As seen in the side view of FIG. 5, the FR patches 303 are located between a first substrate 309 and a second substrate 312. A patch antenna 115 including a slot rotated at 45 degrees is located on the side of the second substrate 312 opposite the FR patches 303. The rotated slot provides RHCP gain. The dimensions of the slot are different than

those in FIG. 2A to account for the needs of the GPS design. A metal ground plane 306 is located on the side of the first substrate 309 that is opposite the FR patches 303. A coaxial feeding line 315 passes through the ground plane 306, first substrate 309, FR patches 303, and second substrate 312 to provide a connection to the patch antenna 115. The GPS antenna was implemented with the first substrate 309 between the FR patches 303 and the ground plane 309 comprising a thermoset microwave material (e.g., Rogers TMM® 10i) with a thickness of 5.08mm, ε_r=9.8, and tanδ=0.002 and the second substrate 312 between the FR patches 303 and the patch antenna 115 comprising a filled PTFE (random glass or ceramic) composite laminate (e.g., Rogers RT/duroid® 6010LM) with a thickness of 0.645mm, ε_r=10.2, and tanδ=0.0023.

[0024] Referring to FIG. 6A, shown is a plot of the simulated radiation pattern produced by the 1.575 GHz antenna on the FR-RIS 300 of FIG.5. As can be seen, the RHCP gain shows a broadside radiation pattern. The electric field vector of the RHCP rotates in a clock wise direction as the wave advances in the direction of propagation. FIG. 6B is a plot of the return loss and FIG. 6C is a plot of the axial ratio for the GPS antenna design. The simulation results are summarized in the table of FIG. 6D. The GPS rotated slot antenna on the FR-RIS 300 provides a 10dB bandwidth of 30 MHz and a 3dB axial ratio bandwidth of 9 MHz.

[0025] The GPS antenna design was implemented with a first substrate 309 of Rogers TMM® 10i with a thickness of 5.08mm and a second substrate 312 of Rogers RT/duroid® 6010LM with a thickness of 0.645mm. The substrates 309/312 include vias (or openings) that allow the coaxial feeding line 315 to pass through. FR patches 303 were formed on one side of the first substrate 309 and a ground plane (or PEC) 306 was formed on the other side of the first substrate 309. FIG. 7A includes images of the FR patches 303 disposed on the top of the first substrate 309 and the ground plane 306 disposed on the bottom of the first substrate 309. The patch antenna 115 with the 45° rotated slot was formed on one side of the second substrate 312. FIG. 7B includes images of the antenna patch 115 disposed on the top of the second substrate 312 and the bare bottom of the second substrate 312.

[0026] As illustrated in FIG. 7C, the second substrate 312 was placed on the first substrate 309 with the bare bottom of the second substrate 312 adjacent to the FR patches 312 on the top of the first substrate 309. The coaxial feeding line 315 passes through the vias or openings in the first and second substrates 309/312 for connection to the patch antenna 115. A SMA (subminiature version A) connector provides a detachable connection to the coaxial feeding line 315. The assembled GPS antenna is shown in FIG. 7D. The device under test (DUT) setup for testing of the fabricated GPS antenna, and the horn antenna used in the measurement setup, are pictured in FIG. 7E.

[0027] Referring now to FIGS. 8A-8D, shown are the measurement results of the fabricated GPS antenna of FIGS. 5 and 7A-7D. FIG. 8A compares the simulated and measured radiation patterns (total gain) in the XZ-plane (top) and YZ-plane (bottom). The total gain of the radiation patterns includes both right-hand circular polarization (RHCP) gain (or co-polarization gain) and left-hand circular polarization (LHCP) gain (or cross-polarization gain). FIG. 8B is a plot of the return loss and FIG. 8C is a plot of the axial ratio comparing the measured and simulated results for the GPS antenna design. The table in FIG. 8D summarizes the simulated and measured results, which are well matched.

[0028] It should be emphasized that the above-described embodiments of the present disclosure are merely possible examples of implementations set forth for a clear understanding of the principles of the disclosure. Many variations and modifications may be made to the above-described embodiment(s) without departing substantially from the spirit and principles of the disclosure. All such modifications and variations are intended to be included herein within the scope of this disclosure and protected by the following claims.

[0029] The term "substantially" is meant to permit deviations from the descriptive term that don't negatively impact the intended purpose. Descriptive terms are implicitly understood to be modified by the word substantially, even if the term is not explicitly modified by the word substantially.

[0030] It should be noted that ratios, concentrations, amounts, and other numerical data may be expressed herein in a range format. It is to be understood that such a range format

is used for convenience and brevity, and thus, should be interpreted in a flexible manner to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. To illustrate, a concentration range of "about 0.1% to about 5%" should be interpreted to include not only the explicitly recited concentration of about 0.1 wt% to about 5 wt%, but also include individual concentrations (*e.g.*, 1%, 2%, 3%, and 4%) and the sub-ranges (*e.g.*, 0.5%, 1.1%, 2.2%, 3.3%, and 4.4%) within the indicated range. The term "about" can include traditional rounding according to significant figures of numerical values. In addition, the phrase "about 'x' to 'y'" includes "about 'x' to about 'y'".

CLAIMS

Therefore, at least the following is claimed:

1. An antenna, comprising:

a fractal rectangular reactive impedance surface (FR-RIS) comprising a plurality of fractal rectangular (FR) patches having an outer edge defined by a fractal rectangular pattern that is repeated along each side of inner FR patches of the plurality of FR patches, where the fractal rectangular pattern of one of the plurality of FR patches matches with the fractal rectangular pattern of an adjacent FR patch of the plurality of FR patches; and

a planar antenna disposed over the FR-RIS.

2. The antenna of claim 1, wherein the fractal rectangular pattern comprises a rectangular tab extending outward from each side of the inner FR patches and a corresponding rectangular recess extending inward from each side of the inner FR patches.

3. The antenna of any of claims 1 and 2, wherein the FR-RIS comprises a gap defined by the fractal rectangular pattern of adjacent FR patches of the plurality of FR patches, wherein the gap distance between the adjacent FR patches substantially constant.

4. The antenna of claim 3, wherein a capacitance of the FR-RIS is based at least in part upon a length of the outer edge of the plurality of FR patches.

5. The antenna of any of claims 1-4, wherein the FR-RIS comprises a substrate disposed between the planar antenna and the plurality of FR patches.

6. The antenna of claim 5, wherein the planar antenna is coupled to a feeding line that passes through the plurality of FR patches and the substrate.

7. The antenna of claim 6, wherein the feeding line is a coaxial feeding line.

8. The antenna of any of claims 1-7, wherein the plurality of FR patches are disposed on a first side of a substrate, and the FR-RIS comprises a ground plane disposed on a second side of the substrate opposite the plurality of FR patches.

9. The antenna of claim 8, wherein an inductance of the FR-RIS is based at least in part upon a distance between the ground plane and the plurality of FR patches.

10. The antenna of claim 9, wherein the inductance of the FR-RIS is further based upon a shape of the FR patches.

11. The antenna of any of claims 1-10, wherein the planar antenna is a patch antenna.

12. The antenna of claim 11, wherein the patch antenna comprises a slot.

13. The antenna of claim 12, wherein the slot is rotated with respect to the patch antenna.

14. The antenna of claim 13, wherein the slot is rotated at an angle of 45 degrees with respect to edges of the plurality of FR patches.

15. The antenna of any of claims 1-14, wherein an outer edge of the FR-RIS defines a rectangular shape.

16. The antenna of claim 15, wherein the rectangular shape is a square.

17. The antenna of claim 15, wherein outer FR patches of the plurality of FR patches are distributed along the outer edge of the FR-RIS, the outer FR patches trimmed to provide the rectangular shape.

18. The antenna of claim 15, wherein the patch antenna disposed over the FR-RIS has a rectangular shape that is substantially aligned with the rectangular shape of the FR-RIS.

19. The antenna of claim 18, wherein the patch antenna is smaller than the FR-RIS.

20. The antenna of claim 1, wherein the fractal rectangular pattern of adjacent FR patches of the plurality of FR patches are interdigitated.

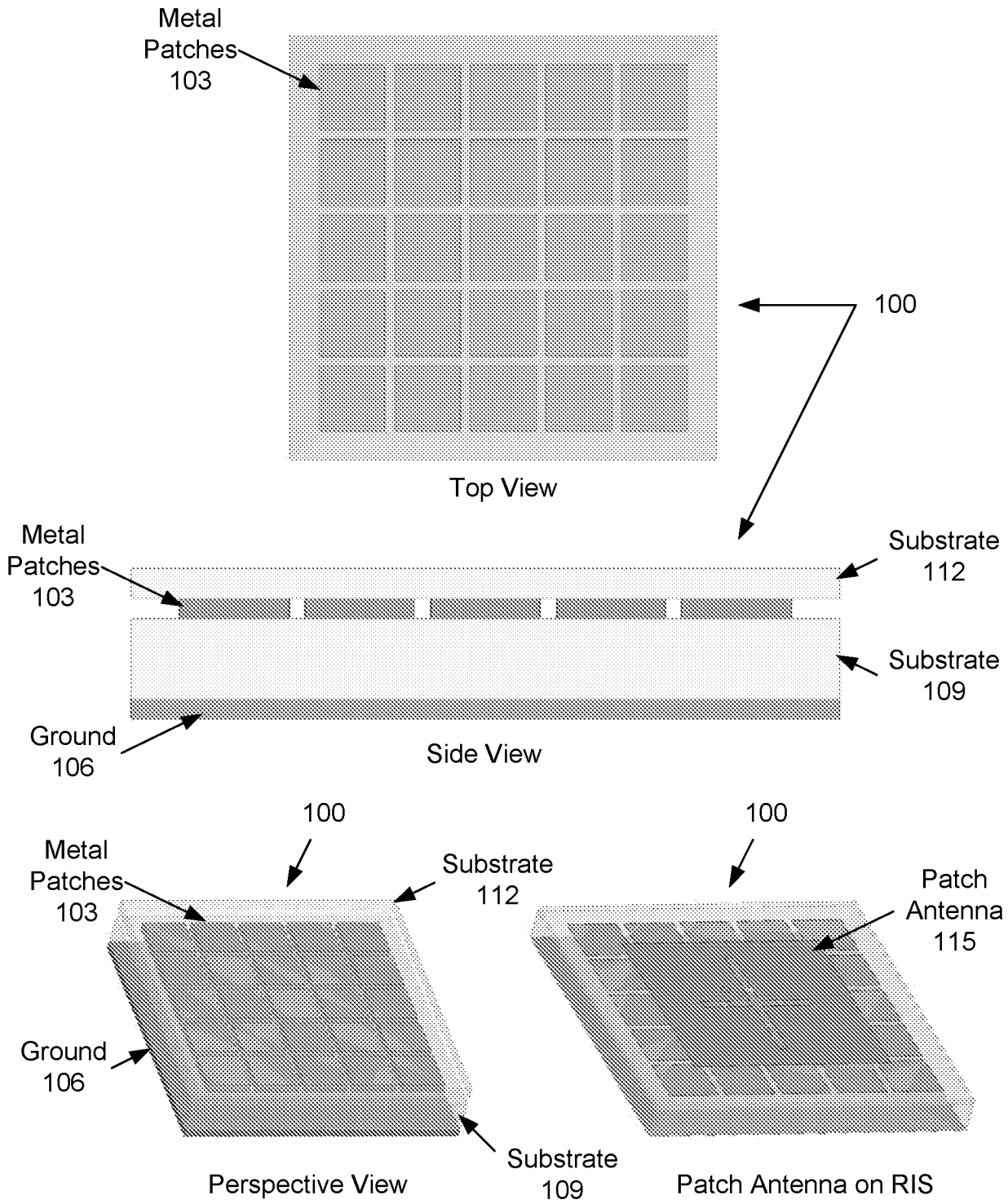

Metal Patches 103
100
Top View
Metal Patches 103
Substrate 112
Substrate 109
Ground 106
Side View
100
100
Metal Patches 103
Substrate 112
Patch Antenna 115
Ground 106
Substrate 109
Perspective View
Patch Antenna on RIS

FIG. 1

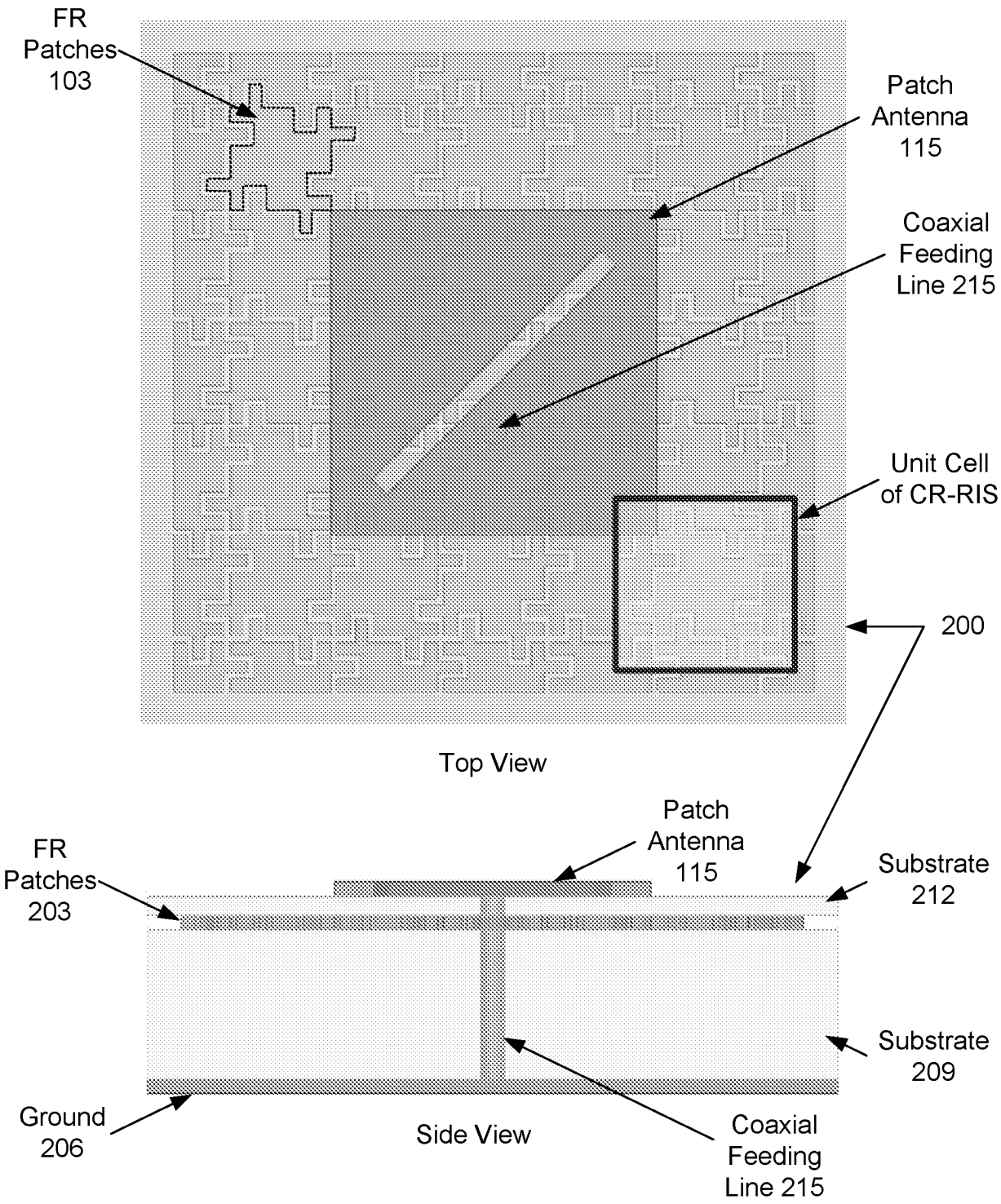

FR Patches 103
Patch Antenna 115
Coaxial Feeding Line 215
Unit Cell of CR-RIS
200
Top View
FR Patches 203
Patch Antenna 115
Substrate 212
Substrate 209
Ground 206
Side View
Coaxial Feeding Line 215

FIG. 2A

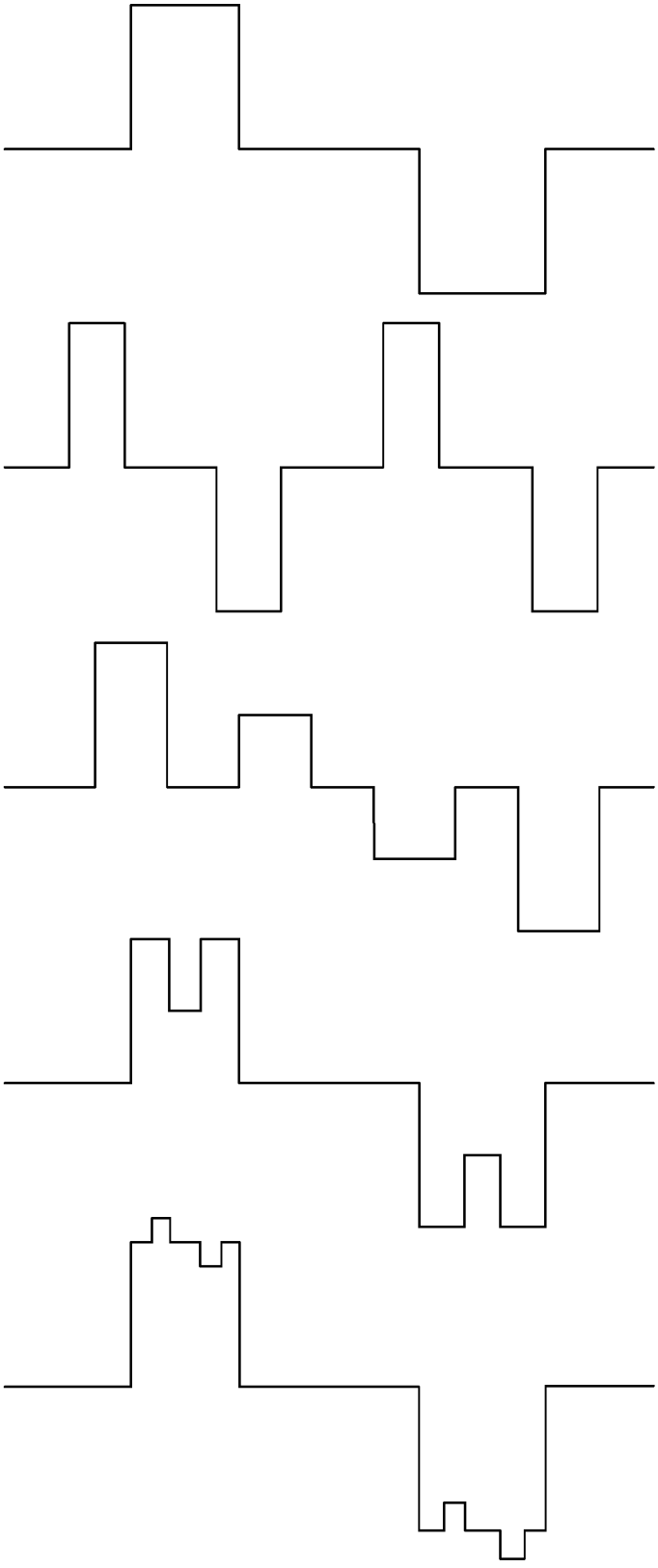


FIG. 2B

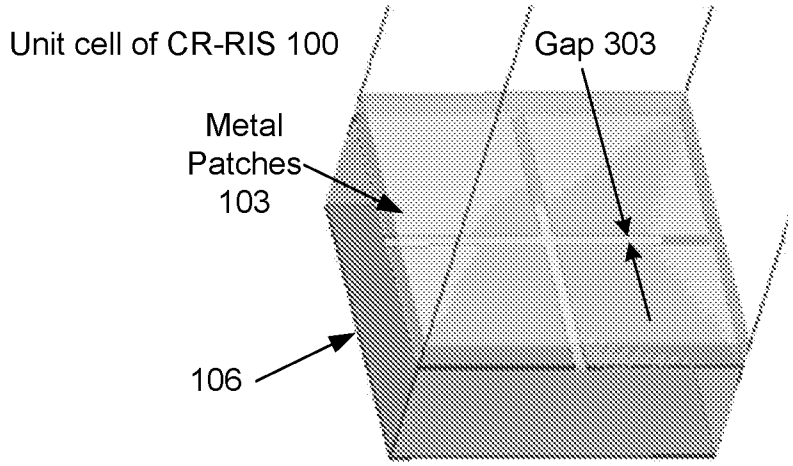
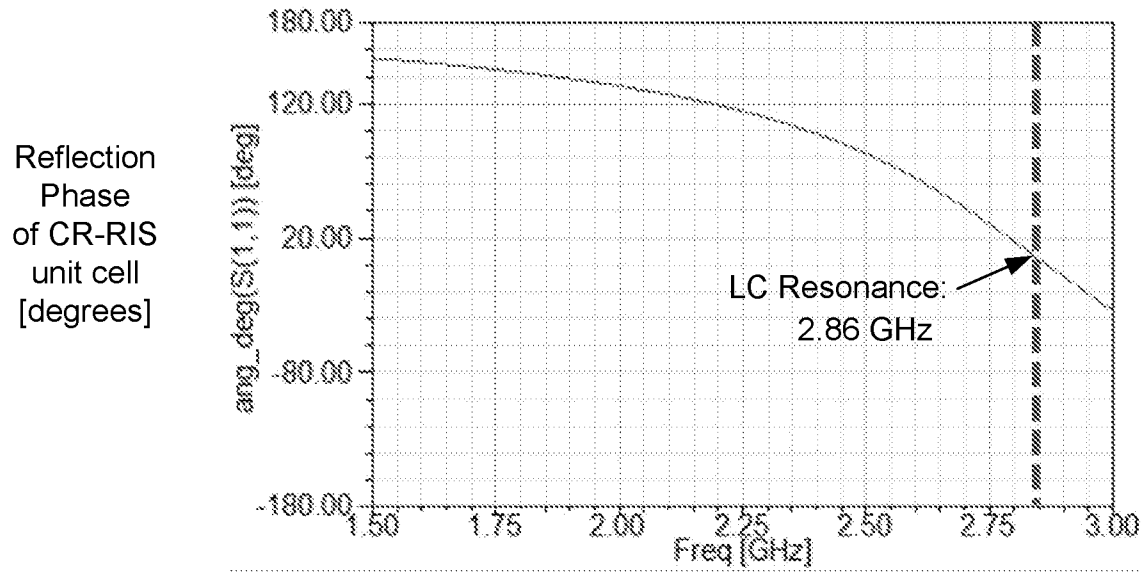
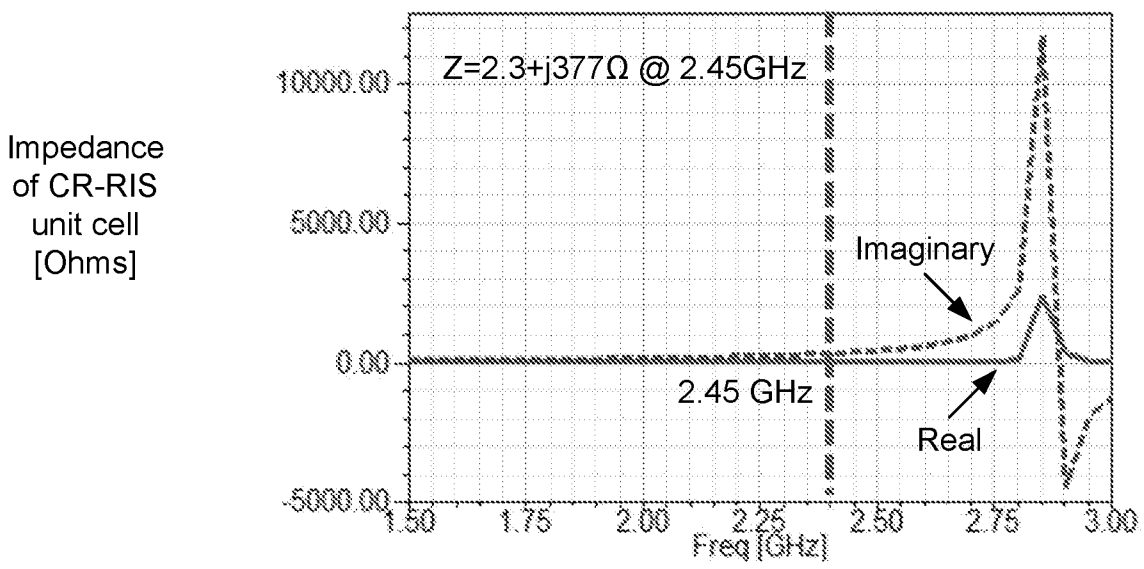

Unit cell of CR-RIS 100
Gap 303
Metal Patches 103
106

FIG. 3A


Reflection Phase of CR-RIS unit cell [degrees]
180.00
120.00
20.00
-80.00
-180.00
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Freq [GHz]
LC Resonance: 2.86 GHz


Impedance of CR-RIS unit cell [Ohms]
Z=2.3+j377Ω @ 2.45GHz
10000.00
5000.00
0.00
-5000.00
Imaginary
2.45 GHz
Real
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Freq [GHz]

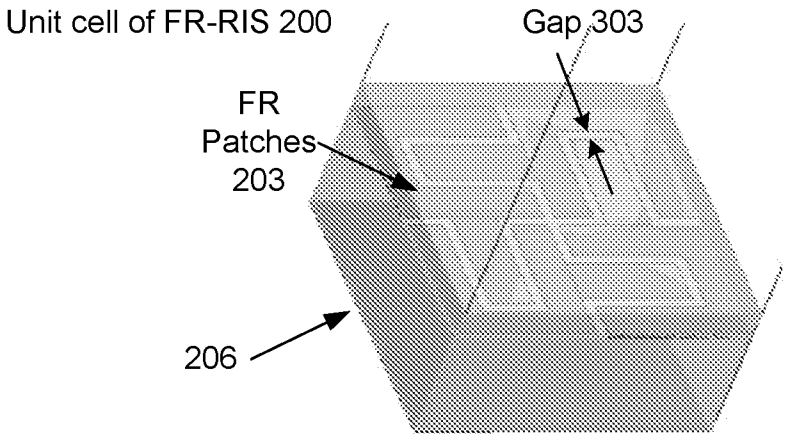
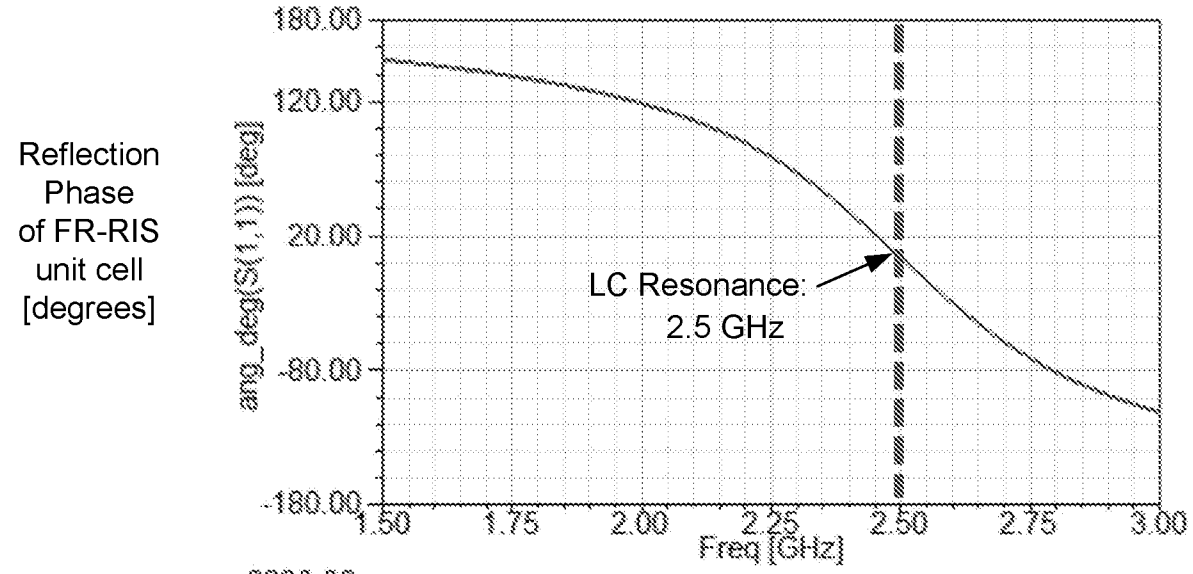
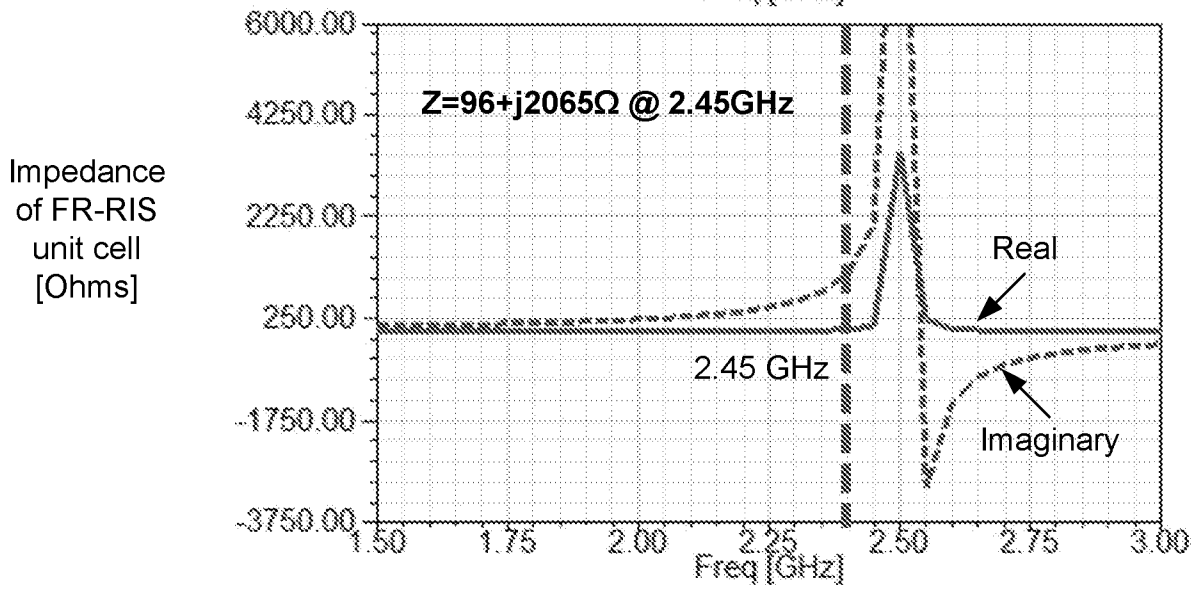

Unit cell of FR-RIS 200
Gap 303
FR Patches 203
206

FIG. 3B


Reflection Phase of FR-RIS unit cell [degrees]
ang_deg(S(1,1)) [deg]
180.00
120.00
20.00
-80.00
-180.00
LC Resonance: 2.5 GHz
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Freq [GHz]


Impedance of FR-RIS unit cell [Ohms]
6000.00
4250.00
2250.00
250.00
-1750.00
-3750.00
Z=96+j2065Ω @ 2.45GHz
Real
2.45 GHz
Imaginary
1.50
1.75
2.00
2.25
2.50
2.75
3.00
Freq [GHz]

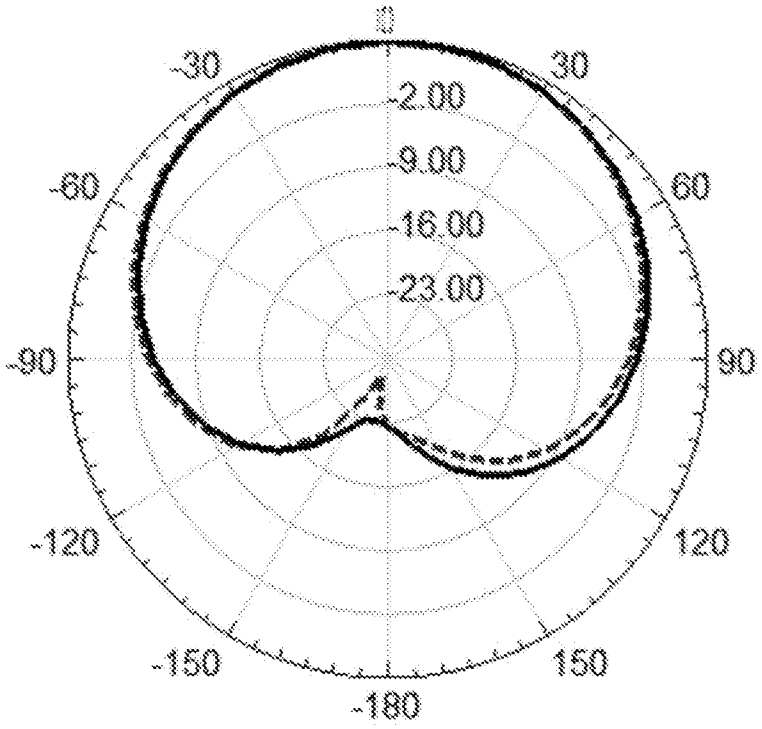

0
30
60
90
120
150
-180
-150
-120
-90
-60
-30
-2.00
-9.00
-16.00
-23.00

FIG. 4A

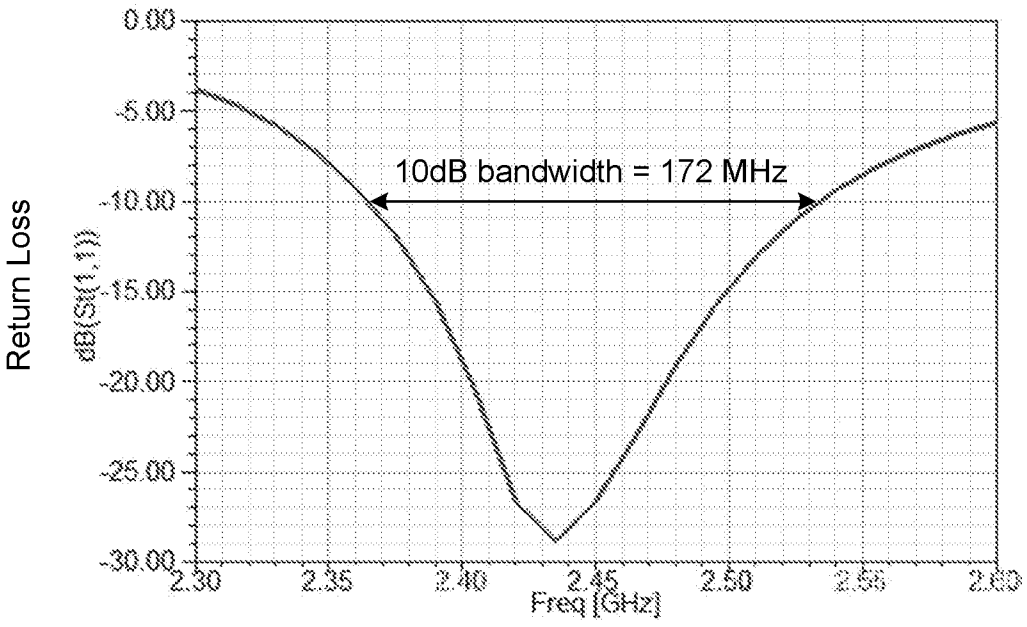

0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
Return Loss
dB(S(1,1))
10dB bandwidth = 172 MHz
2.30
2.35
2.40
2.45
2.50
2.55
2.60
Freq [GHz]

FIG. 4B

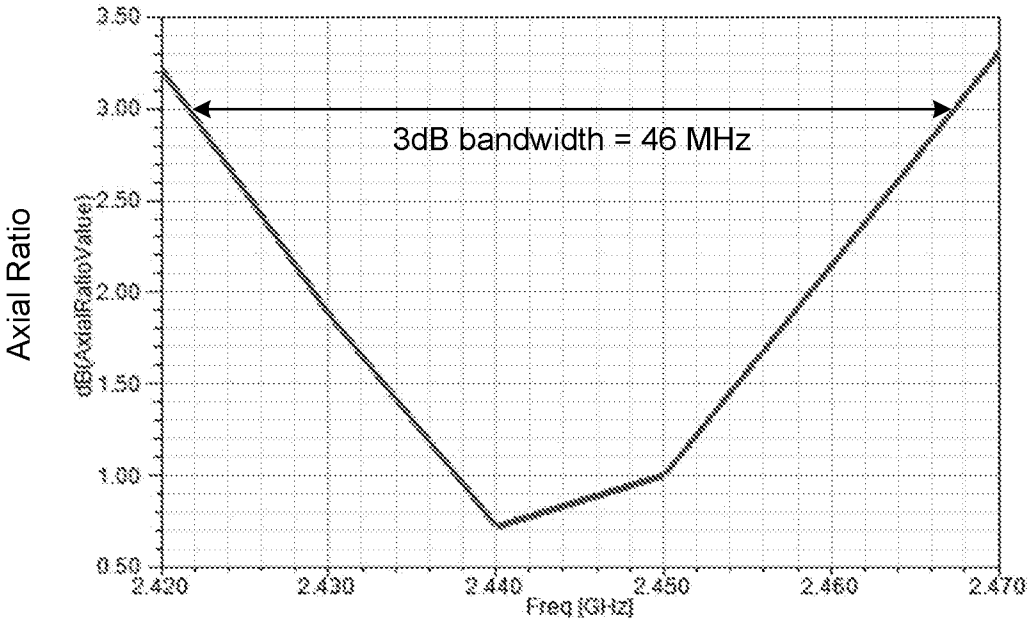


FIG. 4C

Parameters	Simulation
Center Frequency	2.45 GHz
Return Loss	27dB
10 dB Bandwidth	172MHz (2.36GHz – 2.53GHz)
Axial Ratio	1 dB
3 dB Axial Ratio Bandwidth	46MHz (2.42GHz – 2.47GHz)
Polarization	RHCP
Radiation Pattern	Broadside
Gain	4.8dBic

FIG. 4D

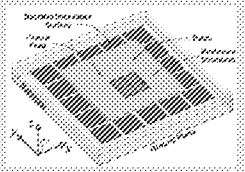
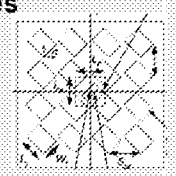
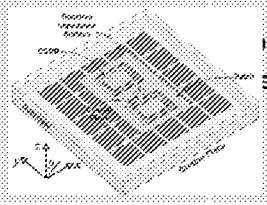
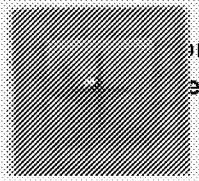
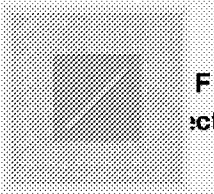
Antenna figure	RIS structure	Resonant Freq.	Designed Patch Size	Substrate Size	10 dB Bandwidth	3 dB Axial Ratio Bandwidth	Gain
[1] Mushroom structure 	Conventional Rectangular RIS	2.58GHz	20.6mm x 20.6mm ($0.355\lambda_g$ x $0.355\lambda_g$)	36mm x 36mm	-	1.6%	2.98 dBic
[2] 45 degrees rotated slot 	45 degrees-rotated Conventional Rectangular RIS	2.3GHz	19mm x 19mm ($0.38\lambda_g$ x $0.38\lambda_g$) =$0.144\lambda_g^2$	100mm x 100mm	320MHz (14%)	-	0 dBic
[3] Two CSRR on patch 	Conventional Rectangular RIS	2.8GHz	20.6mm x 20.6mm ($0.355\lambda_g$ x $0.355\lambda_g$) =$0.126\lambda_g^2$	36mm x 36mm	-	-	4 dBic
[4] Cross-slots on patch 	Conventional Rectangular RIS	2.5GHz	20.6mm x 20.6mm ($0.355\lambda_g$ x $0.355\lambda_g$)	36mm x 36mm	3.84%	-	3.2 dBic
Rotated Slot Antenna of FIG. 2A 	**Fractal Rectangular RIS**	**2.45GHz (Wi-Fi)**	**16.5mm x 16.5mm ($0.317\lambda_g$ x $0.317\lambda_g$) =$0.1\lambda_g^2$ (20%reduction)**	**36mm x 36mm**	**172MHz (6.9%)**	**46MHz (1.8%)**	**4.85 dBic**

FIG. 4E

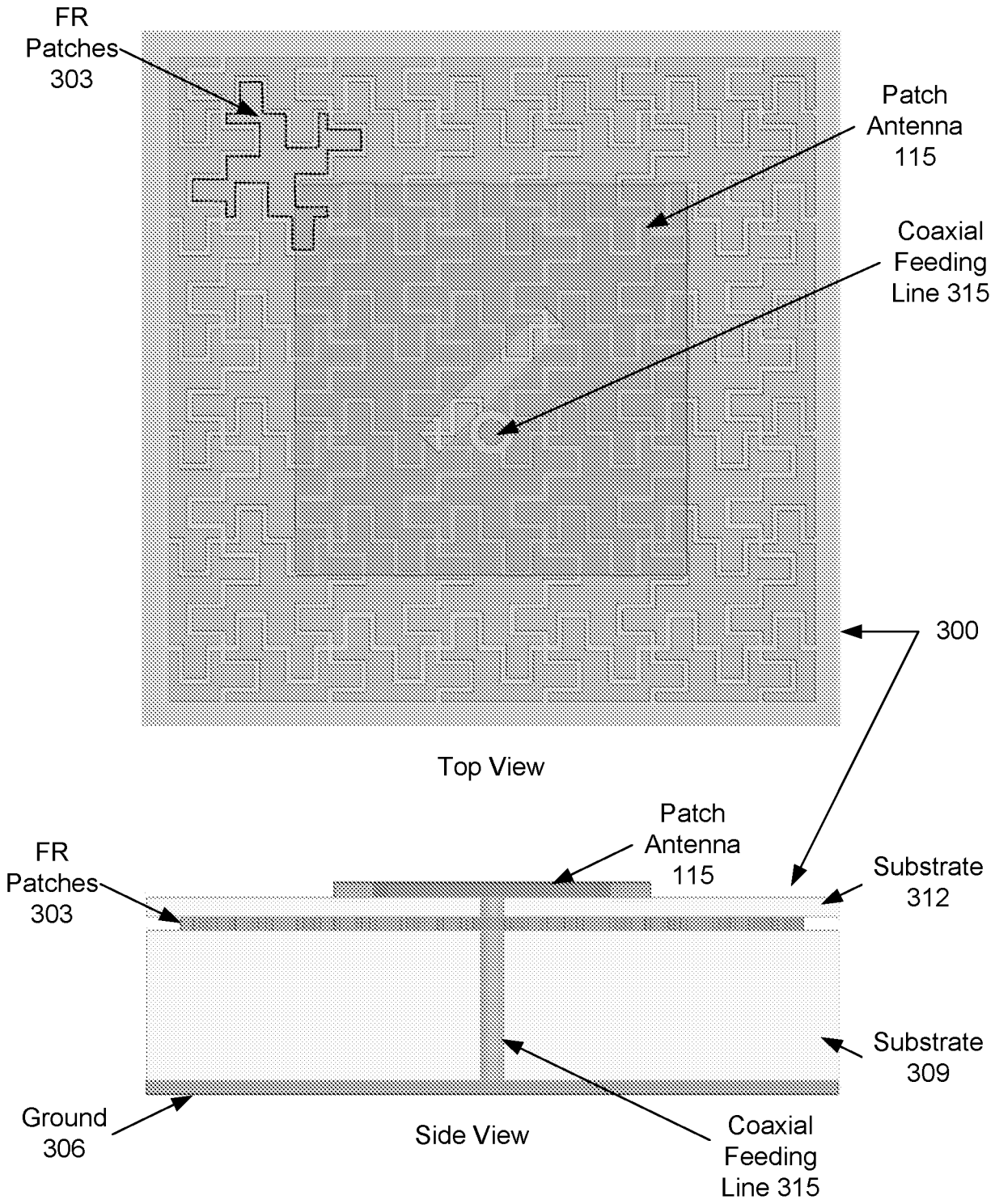

FR
Patches
303
Patch
Antenna
115
Coaxial
Feeding
Line 315
300
Top View
Patch
Antenna
115
FR
Patches
303
Substrate
312
Substrate
309
Ground
306
Side View
Coaxial
Feeding
Line 315

FIG. 5

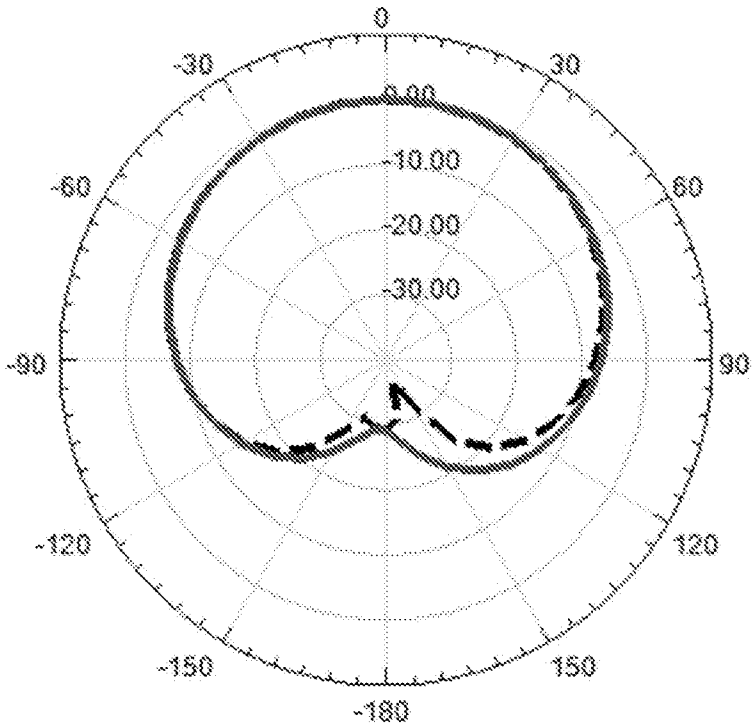

0
30
60
90
120
150
-180
-150
-120
-90
-60
-30
-0.00
-10.00
-20.00
-30.00

FIG. 6A

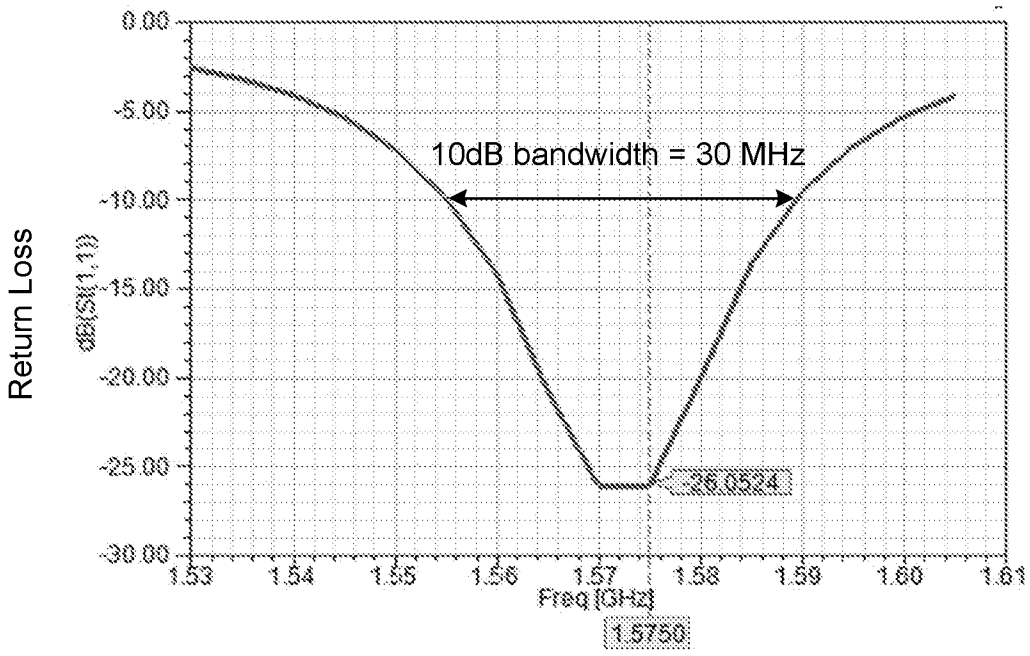

Return Loss
dB(S(1,1))
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
10dB bandwidth = 30 MHz
-26.0524
1.53
1.54
1.55
1.56
1.57
1.58
1.59
1.60
1.61
Freq [GHz]
1.5750

FIG. 6B

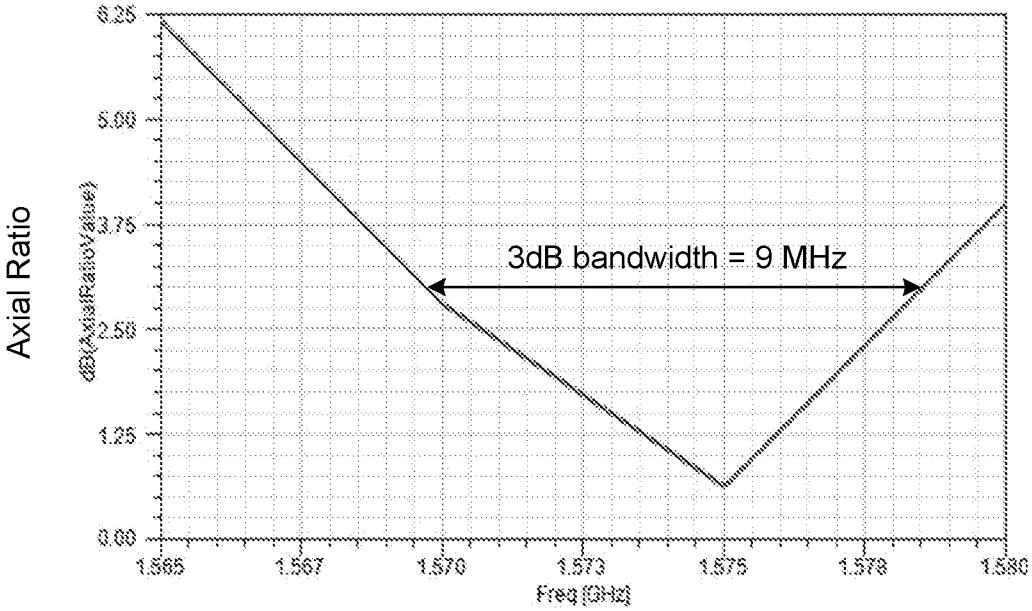


FIG. 6C

Parameters	Simulation
Center Frequency	1.575 GHz
Return Loss	26dB
10 dB Bandwidth	30MHz (19%)
Axial Ratio	0.6 dB
3 dB Axial Ratio Bandwidth	9MHz (0.6%)
Polarization	RHCP
Radiation Pattern	Broadside
Gain	0.025dBic

FIG. 6D

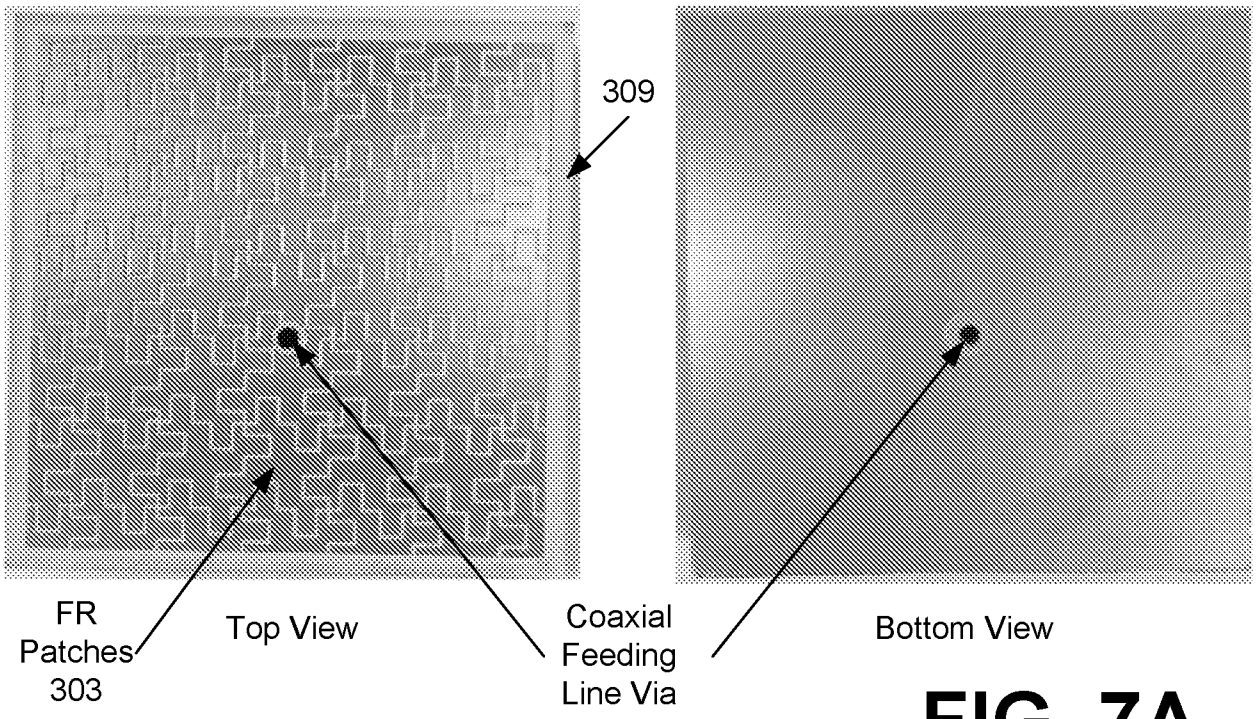

309
FR Patches 303
Top View
Coaxial Feeding Line Via
Bottom View

FIG. 7A

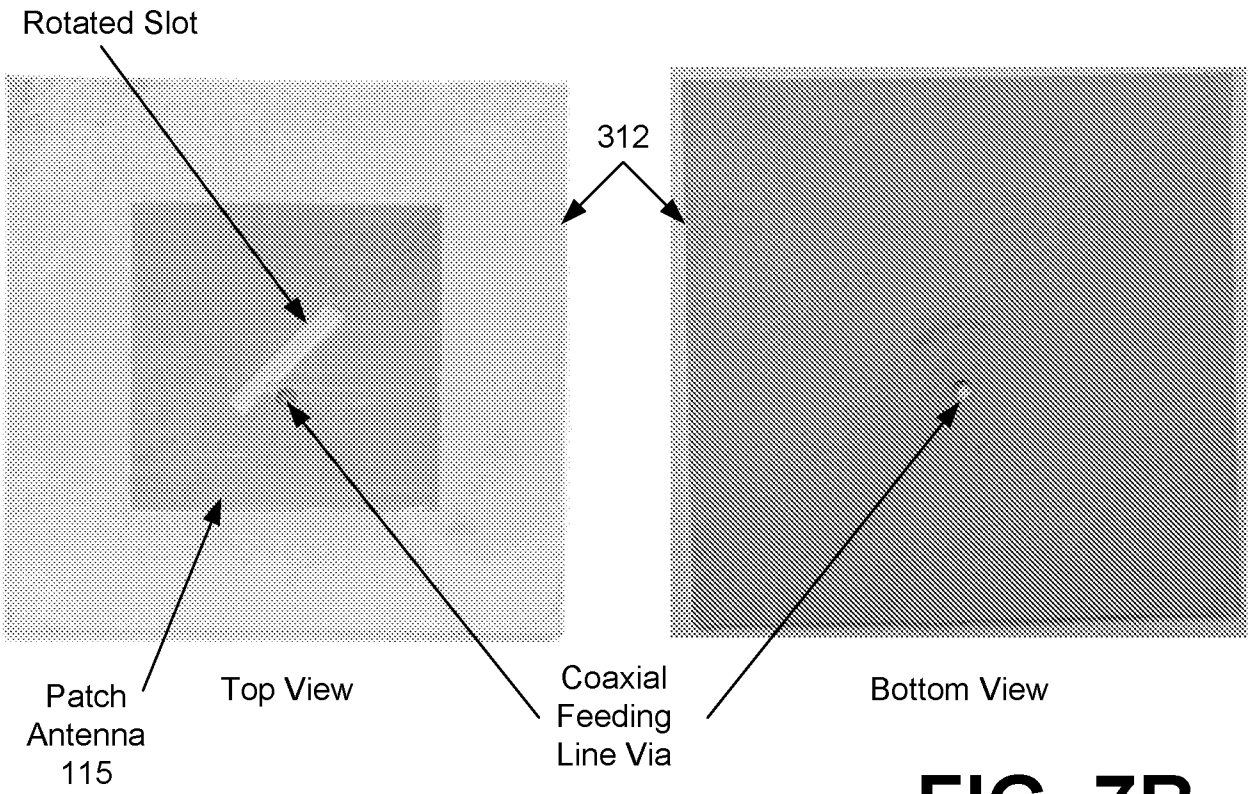

Rotated Slot
312
Patch Antenna 115
Top View
Coaxial Feeding Line Via
Bottom View

FIG. 7B

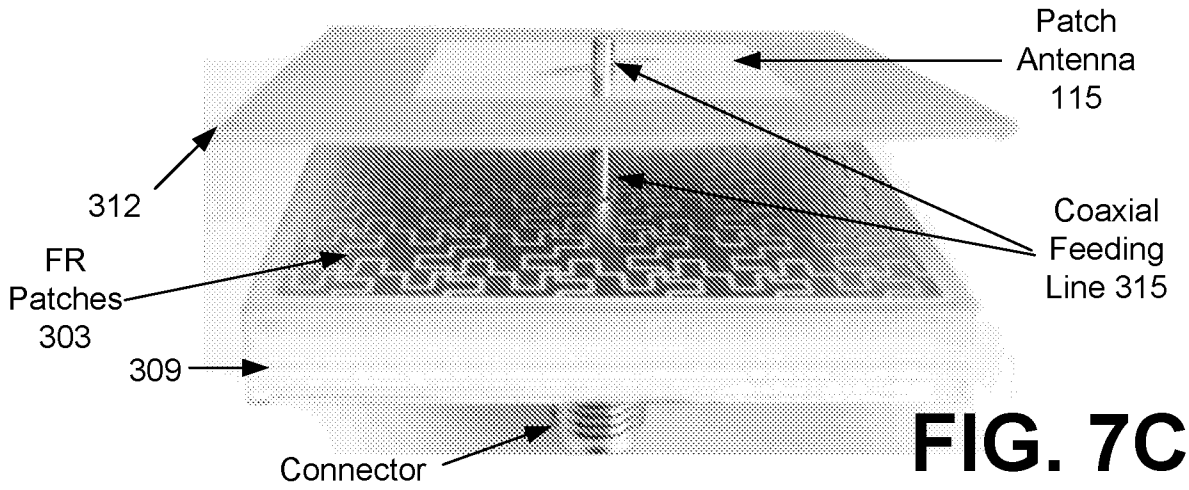


FIG. 7C

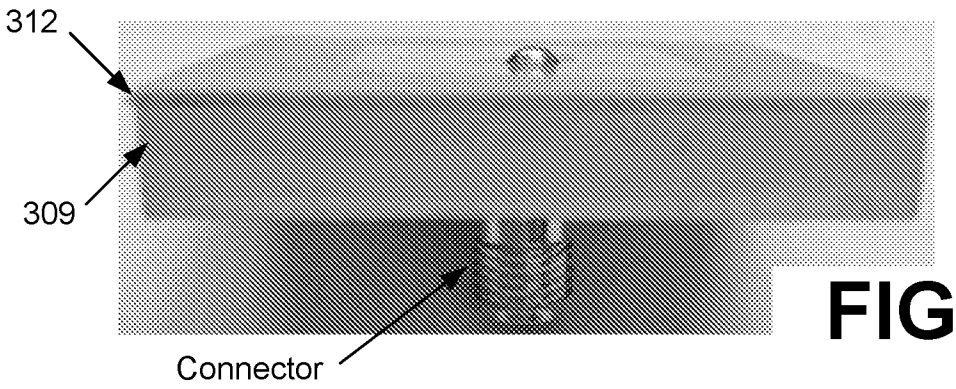
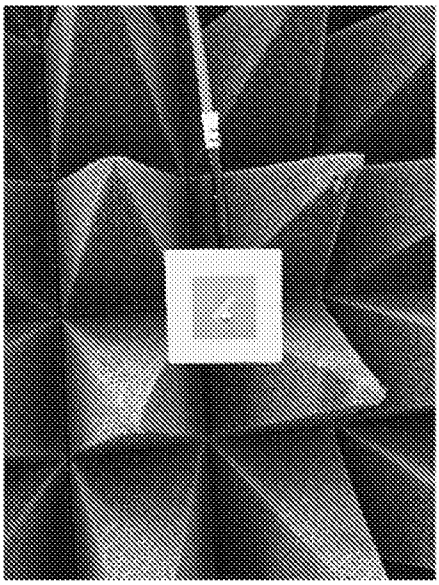
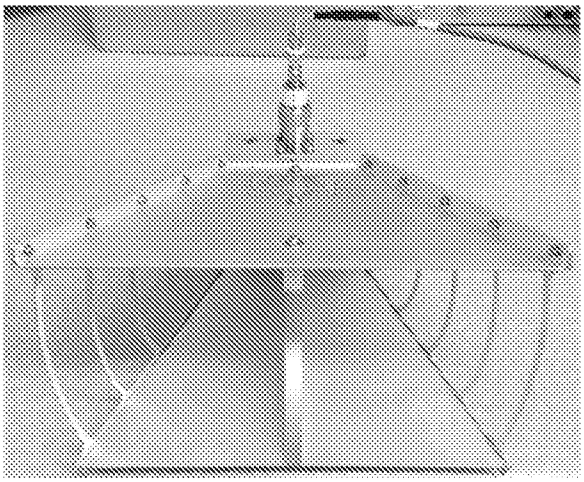


FIG. 7D



DUT



Horn Antenna for Measurement

FIG. 7E

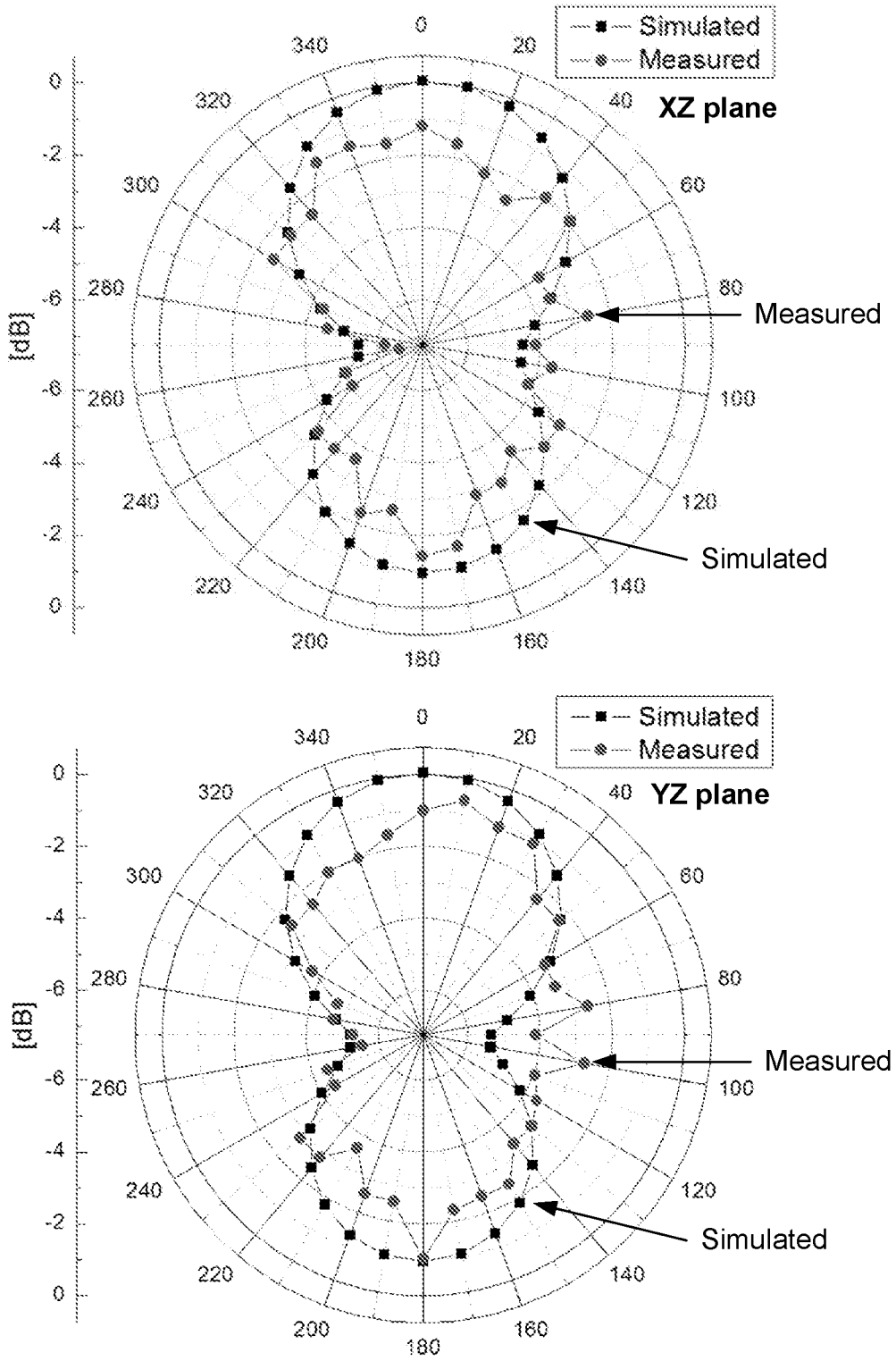

Simulated
Measured
XZ plane
Measured
Simulated
[dB]
0
-2
-4
-6
-6
-4
-2
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
Simulated
Measured
YZ plane
Measured
Simulated
[dB]

FIG. 8A

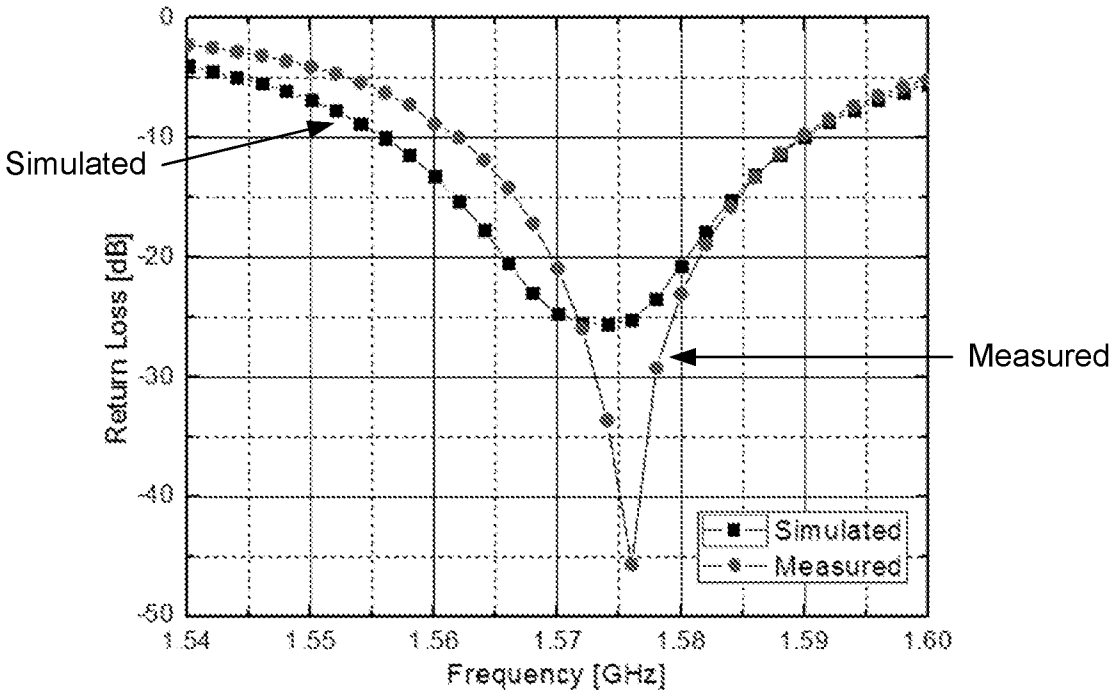

Simulated
Measured
Return Loss [dB]
0
-10
-20
-30
-40
-50
1.54
1.55
1.56
1.57
1.58
1.59
1.60
Frequency [GHz]
Simulated
Measured

FIG. 8B

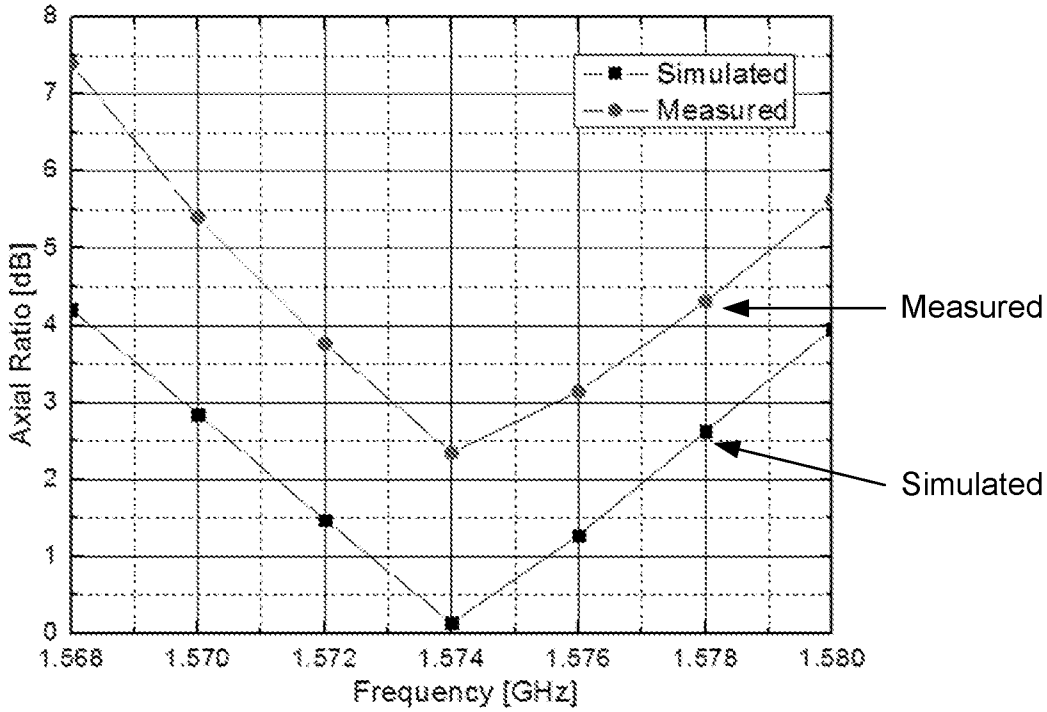

Axial Ratio [dB]
0
1
2
3
4
5
6
7
8
1.568
1.570
1.572
1.574
1.576
1.578
1.580
Frequency [GHz]
Simulated
Measured
Measured
Simulated

FIG. 8C

Parameters	Simulation	Measurement
Resonant Frequency	1.575 GHz	1.575 GHz
Return Loss	24.8 dB	42.2 dB
10dB Bandwidth	30 MHz	28 MHz
Axial Ratio	0.5321 dB	2.34 dB
3dB Axial Ratio	9 MHz	2.5 MHz
Gain	0.045 dB	-1 dB

FIG. 8D

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/027552

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01Q 1/38; H01Q 1/00; H01Q 1/48; H01Q 9/04; H01Q 9/16; H01Q 11/10 (2017.01)
CPC - H01Q 1/38; H01Q 1/00; H01Q 1/48; H01Q 9/04; H01Q 9/16; H01Q 11/10 (2017.02)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 343/700MS; 343/795; 343/846; 343/792.5 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2011/0273319 A1 (MOSSALLAEL) 10 November 2011 (10.11.2011) entire document	1-4, 20
A	US 2008/0180341 A1 (COHEN) 31 July 2008 (31.07.2008) entire document	1-4, 20
A	US 2002/0149519 A1 (VARADAN et al) 17 October 2002 (17.10.2002) entire document	1-4, 20
A	US 2013/0131752 A1 (CARDIAC PACEMAKERS, INC.) 23 May 2013 (23.05.2013) entire document	1-4, 20
A	US 6,140,975 A (COHEN) 31 October 2000 (31.10.2000) entire document	1-4, 20
A	US 2009/0207087 A1 (FANG et al) 20 August 2009 (20.08.2009) entire document	1-4, 20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 June 2017	26 JUN 2017
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/027552

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

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

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

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 5-19
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

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

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

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

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

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

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

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.