



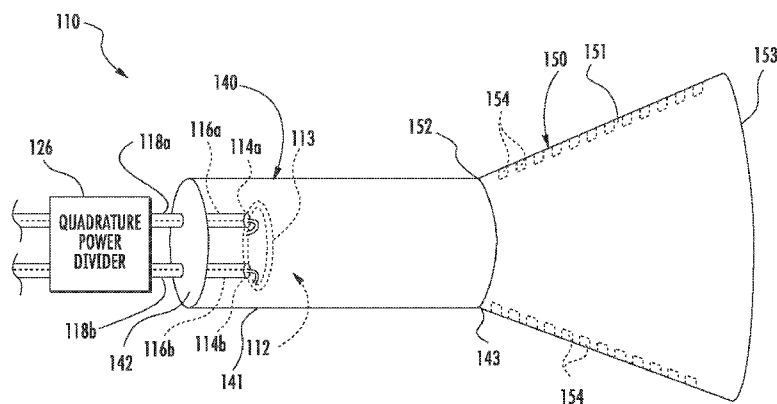
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(54) **Title:** WIRELESS COMMUNICATIONS DEVICE HAVING LOOP WAVEGUIDE TRANSDUCER WITH SPACED APART COUPLING POINTS AND ASSOCIATED METHODS



(57) **Abstract:** A wireless communications device may include wireless communications circuitry and a waveguide transducer coupled to the wireless communications circuitry. The waveguide transducer may include a loop electrical conductor having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points. The waveguide transducer may also include a feed assembly that may include at least one waveguide feed, and a feed network coupled between the at least one waveguide feed and the plurality of coupling points. The waveguide transducer may further include a waveguide surrounding the loop electrical conductor and extending outwardly therefrom. The waveguide may include a tubular body having an open end and an opposing closed end carrying the loop electrical conductor.

WIRELESS COMMUNICATIONS DEVICE HAVING LOOP WAVEGUIDE TRANSDUCER WITH SPACED APART COUPLING POINTS AND ASSOCIATED METHODS

5 **Field of the Invention**

The present invention relates to the field of communications, and more particularly, to loop type antennas, circular polarization, dual polarization and related methods.

10 Background of the Invention

The use of satellite communications has increased the demand for circularly polarized antennas and for dual polarization antennas. For instance, many of the satellite transponders in use today carry two programs on the same frequency by using separate polarizations. Thus, single antenna structure may be called upon to simultaneously receive two polarizations, or perhaps to transmit in one polarization and receive in another. The single antenna structure should therefore separate the two polarization channels, to a high degree of isolation.

It is possible to have dual linear or dual circular polarization channel diversity. That is, a frequency may be reused if one channel is vertically polarized and the other horizontally polarized. Or, a frequency can also be reused if one channel uses right hand circular polarization (RHCP) and the other left hand circular polarization (LHCP). Polarization refers to the orientation of the E field in the radiated wave, and if the E field vector rotates in time, the wave is then said to be rotationally or circularly polarized.

25 An electromagnetic wave has an electric field that varies as a sine wave within a plane coincident with the line of propagation, and the same is true for the magnetic field. The electric and magnetic planes are perpendicular and their intersection is in the line of propagation of the wave. If the electric-field plane does not rotate (about the line of propagation) then the polarization is linear. If, as a
30 function of time, the electric field plane (and therefore the magnetic field plane) rotates, then the polarization is rotational. Rotational polarization is in general

elliptical, and if the rotation rate is constant at one complete cycle every wavelength, then the polarization is circular.

The polarization of a transmitted radio wave is determined in general by the antennas shape and the type of current flowing on that shape. In general,

5 antenna types may be classified as to dipoles and loops, based on the divergence or curl of current. The canonical forms of the dipole and loop antennas are the line and circle. Of course there can be hybrid antennas that use both divergence and curl. Preferred antenna shapes are often Euclidian, being simple geometric shapes known for optimization through the ages.

10 For example, the monopole antenna and the dipole antenna are two common examples of divergence antennas with linear polarization. A helix antenna is a common example of a hybrid divergence and curl antenna with circular polarization. Another example of a circularly polarized antenna is a crossed array of dipoles fed in phase quadrature, e.g., the “Turnstile”. Linear polarization is usually further
15 characterized as either Vertical or Horizontal. Circular Polarization is usually further classified as either Right Hand or Left Hand.

The dipole antenna has been perhaps the most widely used of all the antenna types. It is of course possible however to radiate from a conductor which is not constructed in a straight line. Approaches to circular polarization in loop antennas
20 appear lesser known, or perhaps even unknown in the purest forms. In spite of the higher gain of the full wave loop vs. the half wave dipole (3.6 dBi vs. 2.1 dBi), dipoles are commonly used for circular polarization needs, as for instance in turnstile arrays. A circle antenna structure can be more suited for circular polarization than an X antenna. Both the dipole turnstile and a single loop antenna are planar, in that their
25 thin structure lies nearly in a single plane.

Many structures are described as loop antennas, but the circle shape best provides the curling motion, and a circle advantageously provides the most area for the least circumference. The resonant loop is a full wave circumference circular conductor, often called a “full wave loop”. The typical prior art full wave loop is
30 linearly polarized, having a radiation pattern that is a two petal rose, with two opposed

lobes normal to the loop plane, and a gain of about 3.6 dBi. Reflectors are often used with the full wave loop antenna to obtain a unidirectional pattern.

Dual linear polarization (simultaneous vertical and horizontal polarization from the same antenna) has commonly been obtained from crossed dipole antennas. For instance, U.S. Pat. No. 1,892,221 to Runge, proposes a crossed dipole system. Polarization diversity was recited. The embodiment shown in FIG. 3 and described on page 2 lines 20-29 also provided circular polarized reception.

U.S. Pat. No. 5,977,921 to Niccolai et al. is directed to an antenna for transmitting and receiving circularly polarized electromagnetic radiation which is configurable to either right-hand or left-hand circular polarization. The antenna has a conductive ground plane and a circular closed conductive loop spaced from the plane, i.e., no discontinuities exist in the circular loop structure. A signal transmission line is electrically coupled to the loop at a first point and a probe is electrically coupled to the loop at a spaced-apart second point. This antenna requires a ground plane and includes a parallel feed structure, such that the RF potentials are applied between the loop and the ground plane. The "loop" and the ground plane are actually dipole half elements to each other, and the invention is related to microstrip antennas.

U.S. Pat. No. 5,838,283 to Nakano is directed to a loop antenna for a circularly polarized wave. Driving power fed may be conveyed to a feeding point via an internal coaxial line and a feeder conductor is transmitted through an I-shape conductor to a C-type loop element disposed in spaced facing relation to a ground plane. By the action of a cutoff part formed on the C-type loop element, the C-type loop element radiates a circularly polarized wave. Dual linear, or dual circular polarization are not however provided.

U.S. Pat. No. 6,522,302 to Iwasaki is directed to a circularly polarized antenna array rather than a single circularly polarized loop element. A circle is among the most elemental of antenna structures, and it is a fundamental single geometry capable of circular polarization.

U.S. Pat. Pub. No. 2008/0136720 to Parsche, the inventor of the present application, discloses a multiple polarization loop antenna which includes a

circularly polarized loop antenna. The circularly polarized loop antenna utilizes a loop electrical conductor and two signal feedpoints along the loop electrical conductor separated by one quarter of the length of the loop circumference for a signal feedpoint phase angle input difference of 90 degrees. Each of the signal feedpoints includes a loop discontinuity, so that at least one signal source coupled thereto provides circular polarization from the loop electrical conductor. The circularly polarized loop antenna provides an increase in gain and decrease in size relative to the dipole turnstile. It can provide two orthogonal polarizations from two isolated ports, and the polarizations may be dual linear or dual circular.

While U.S. Pat. Pub. No. 2008/0136720 represents an exemplary advance in the field of circularly polarized loop antennas, further advances are still desirable. For example, improvement to the degree of circularity of the polarization can help improve antenna performance, and a single antenna structure capable of both circular and linear polarization would be useful in some applications.

Summary of the Invention

In view of the foregoing background, it is therefore an object of the present invention to provide a wireless device having a waveguide transducer that can be configured for different polarizations.

This and other objects, features, and advantages in accordance with the present invention are provided by a wireless communications device that includes wireless communications circuitry, and a waveguide transducer coupled to the wireless communications circuitry. The waveguide transducer includes a loop electrical conductor having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points. The waveguide transducer also includes a feed assembly that includes at least one waveguide feed, and a feed network coupled between the at least one waveguide feed and the plurality of coupling points. The waveguide transducer includes a waveguide surrounding the loop electrical conductor and extending outwardly therefrom. The waveguide includes a tubular body having an open end and an opposing closed end carrying the loop electrical conductor.

Accordingly, the waveguide transducer allows operation using both linear and circular polarization, for example, and provides robust performance.

A method aspect is directed to a method of making a waveguide transducer for use in a wireless communications device. The method includes

5 forming a loop electrical conductor having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points. The method also includes forming a feed assembly by forming a feed network and coupling the feed network between at least one waveguide feed and the plurality of coupling points, and

10 positioning a waveguide to surround the loop electrical conductor and extend outwardly therefrom.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of an embodiment of a wireless communications device in accordance with the present invention wherein the antenna

15 is configured for circular polarization operation.

FIG. 2 is a schematic diagram of an embodiment of a wireless communications device in accordance with the present invention wherein the antenna is configured for simultaneous left hand and right hand circular polarization operation.

FIG. 3 is a schematic diagram of an embodiment of a wireless communications device in accordance with the present invention wherein the antenna

20 is configured for linear polarization operation.

FIG. 4 is a schematic diagram of an embodiment of a wireless communications device in accordance with the present invention wherein the antenna is configured for both horizontal and vertical linear polarization operation.

FIG. 5A is a diagram depicting the antenna of FIG. 1 in a standard radiation pattern coordinate system.

25

FIGs. 5B-5D are graphs depicting the principal plane radiation pattern cuts of the antenna of FIG. 1 in free space.

FIG. 6 is a plot of the voltage standing wave ratio (VSWR) response at

30 a loop port on the antenna of FIG. 1.

FIG. 7 is a plot of the impedance response at a loop port on the antenna of FIG. 1, in Smith Chart format.

FIG. 8 is a schematic diagram of an embodiment of a wireless communications device in accordance with the present invention including a
5 waveguide transducer.

FIG. 9 is an enlarged top view of the waveguide transducer of FIG. 8.

FIG. 10 is a schematic diagram of another embodiment of a wireless communications device in accordance with the present invention including a waveguide transducer.

10 FIG. 11 is a Smith Chart of driving point impedance for the waveguide transducer of FIG. 10.

FIG. 12 is a simulated voltage standing wave ratio graph for the waveguide transducer of FIG. 10.

15 FIG. 13a illustrates the waveguide transducer of FIG. 10 without the horn in a radiation pattern coordinate system.

FIGS. 13b-13d are radiation patterns for the waveguide transducer of FIG. 10 without the horn.

FIGS. 14a-14c are field rotation graphs for the waveguide transducer of FIG. 10 with an applied alternating current.

20 FIG. 15 is a graph of the axial ratio for the waveguide transducer of FIG. 10.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter
25 with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

Like numbers refer to like elements throughout, and prime notation is used to indicate similar elements in alternative embodiments.

Referring initially to FIG. 1, a wireless communications device **10** includes wireless communications circuitry **20** and an antenna **12** coupled to the
5 wireless communications circuitry **20**. The wireless communications device **10** may be a satellite transceiver in some embodiments, and as such, the wireless communications circuitry **20** may include transmitter and/or receiver circuitry.

The antenna **12** comprises a loop electrical conductor **13**, which is preferably circularly shaped. The loop electrical conductor **13** may be a metallic ring,
10 circular wire, tubing hoop, a conductive trace, or may be a hole defined in a metallic surface, as will be appreciated by those of skill in the art. Approximations the circle shape may also be used, such as polygons. The loop electrical conductor **13** has four spaced apart gaps therein which define four respective spaced apart coupling points **14a, 14b, 14c, 14d**. Each of the spaced apart gaps may create a pair of terminals on
15 either side of the gap. The spaced apart coupling points 14a, 14b, 14c, 14d may comprise ports.

The spaced apart coupling points **14a, 14b, 14c, 14d** are separated by one quarter of a length of the circumference of the loop electrical conductor **13**, and the length of the loop electrical conductor itself corresponds to an operating
20 wavelength of the antenna **12**. In particular, good results may be obtained with the circumference of the loop electrical conductor **13** being equal to the operating wavelength of the antenna **12**, although it should be noted that the loop electrical conductor **13** circumference may also be multiples and/or fractions of the operating wavelength.

25 The antenna **12** includes a feed assembly **15**, to relay signals to and from the wireless communications circuitry **20**, as well as to configure the antenna for different modes of operation, as will be explained in detail below. The feed assembly **15**, in turn, includes an antenna feed **18** which is coupled to the wireless communications circuitry **20**. The antenna feed **15** in turn is coupled to each of four
30 signal feed lines **16a, 16b, 16c, 16d** at a common node **19**. The signal feed lines **16a,**

16b, 16c, 16d are illustratively delay lines, but it should be understood that they need not be. Each delay line **16a, 16b, 16c, 16c** is coupled to a respective one of the coupling points **14a, 14b, 14c, 14d**. The feed assembly **15** divides radio frequency power four ways and delivers the divided power at different relative phases. Baluns **17a, 17b, 17c, 17d** may be provided suppress common mode currents on feed assembly **15**, such as ferrite beads. Baluns **15** may also be balun transformers to the match coupling point **14a, 14b, 14c, 14d** impedances to the feed assembly **15**, if desired.

As can be appreciated by those in the art, FIG. 1 depicts the delay lines **16a, 16b, 16c, 16c** to be connected in parallel at the common node **19**. This will provide equal power division into the four delay lines **16a, 16b, 16c, 16c** when the impedance referred by the four delay lines **16a, 16b, 16c, 16d** are equal. Of course other means of power division may also be used at the common node **19**, such as series connections of the delay lines **16a, 16b, 16c, 16c**, any combination of series and or parallel connections, a transformer with multiple windings, a branch line coupler, etc. as those in the art can appreciate.

Since the length of each delay line **16a, 16b, 16c, 16d** is illustratively different, each delay line will refer a fraction of the transmit signal to the coupling points **14a, 14b, 14c, 14d** at different relative phase, or in the receive case refer the fractions of the receive signal to antenna feed **18** in a reciprocal fashion to the transmit case. Here, the phases shifted versions of the transmit signal are referred to the coupling points **14a, 14b, 14c, 14c**, or the phase shifted versions of the receive signal are referred to the antenna feed **18**, at 0°, 90°, 180°, and 270° relative phase respectively. The feed assembly **15** may provide equal amplitude excitations in phase quadrature (0, 90, 180, 270 degrees) at the coupling points **14a, 14b, 14c, 14d**. For example, if the wireless communications circuitry **20** provides 1 watt of RF power, then the feed assembly **15** provides ¼ watt of RF power to each of the coupling points **14a, 14b, 14c, 14d** at relative phases of 0, 90, 180 and 270 degrees. This arrangement of phase differences results in a signal being transmitted with circular polarization, in particular right hand circular polarization is produced out of the page. This is because

the equal amplitude quadrature phase excitations at the spaced apart coupling points **14a, 14b, 14c, 14d** imparts a traveling wave current distribution on the loop electrical conductor **13**.

The traveling wave current distribution will be further explained. A
 5 traveling wave current distribution means that the loop electrical conductor **13** has a sine wave current distribution which is moving around the circumference of the loop circumference at an angular velocity of $\omega = 2\pi f$. So to speak then, two “lumps of current” rotate around the loop electrical conductor **13** circumference. The two current maxima are opposite each other at all times. Since the flow of RF electric
 10 currents cause radio waves, and the RF currents are themselves rotating around the loop, then the transmitted wave must spin around its axis, which is circular polarization.

As background, prior art linearly polarized full wave loop antennas have an electrical current distributions on the loop conductor that does *not* spin
 15 around the loop circumference. Rather, the two current maxima stand still in space.

A theory of operation for a circular loop electrical conductor **13** will now be provided. The four equal amplitude quadrature phase excitations would if summed together in an ordinary fashion cancel and become zero, e.g., the vector sum of $1 \angle 0^\circ + 1 \angle 90^\circ + 1 \angle 180^\circ + 1 \angle 270^\circ = 0$. The structure of the circular loop
 20 electrical conductor **13** however has dual properties of: 1) a radiating antenna and 2) a hybrid ring power combiner. So, the circular loop electrical conductor **13** can *hybrid combine* the RF powers at the coupling points **14a, 14b, 14c, 14d** without cancellation, and this produces a traveling wave current distribution. The hybrid power combining properties of the circular loop electrical conductor **13** are as
 25 follows: port **14a** is uncoupled from port **14b**, port **14b** is uncoupled from port **14c**, port **14c** is uncoupled from port **14d**, and port **14d** is uncoupled from port **14a**, or stated as scattering parameters $S_{14a14b} = 0, S_{14b14c} = 0, S_{14c14d} = 0, S_{14d14a} = 0$. The quadrature excitation and hybrid combining in the loop electrical conductor **13** results in the superposition of sines and cosines in an extension of the Pythagorean Identity:

30

$$I_{\text{loop}} = (\sin \theta)^2 + (\cos \theta)^2 + (-\sin \theta)^2 + (-\cos \theta)^2$$

Where I_{loop} is the current on the loop conductor **13**. The sine term corresponds to the 0 degree excitation at coupling point **14a**, the cosine to the 90 degree excitation at **14b**, the $-\sin$ term to the 180 degree excitation at **14c**, and the $-\cos$ term to the 270 degree excitation at **14d**. The traveling wave current distribution transduces a circularly polarized wave as it is moving in a circle.

If the delay lines **16a**, **16b**, **16c**, **16c** are sized such that the phase delay increases in the opposite sense as shown, the circular polarization will be left handed circular polarization produced into the page. So, increasing phase delay (such as more cable length) is introduced in a sense opposite that of the desired circular polarization sense. In addition, as will be appreciated by those of skill in the art, the delay lines **16a**, **16b**, **16c**, **16c** need not cause the delay due to a mere function of their length, and need not have different lengths, but may include suitable phase shifting elements therein so as to produce the desired phase shift. Examples include coaxial cables having different permittivity dielectrics or ferrites, and ladder networks of inductors and capacitors.

Regarding the choice of circular polarization sense, right handed circular polarization may be preferential in the northern hemisphere, and left handed circular polarization may be preferable in the southern hemisphere, due to electron rotation (gyro resonance) in the ionosphere (see also "Ionospheric Radio Propagation", K. Davies. National Bureau of Standards, April 1, 1965).

The far field radiation pattern is the Fourier transform of the current distribution on the loop conductor **13**, so the radiated field of the antenna **12** in the Z direction (normal to the loop plane) has a constant magnitude over time which is described by

$$E = (\cos^2 \omega t + \sin^2 \omega t)^{1/2} = 1,$$

which is the condition for circular polarization. ω is the orientation of the E field about the wave axis, e.g., the polarization angle, and t is time. FIG. 6 depicts the present invention in a standard radiation pattern coordinate system, and examples of

the principal plane far field radiation pattern cuts (XY, YZ, ZX) for the present invention circularly polarized loop antenna are depicted in FIGs. 5B-5D. These patterns were obtained by moment method numerical electromagnetic modeling, and are for operation in free space. Total fields are plotted. The plotted quantity is

5 directivity. The units are dBic, expressed in decibels relative to an isotropic radiator that is circularly polarized. If the antenna is efficiently matched and tuned the FIGs. 5B-5D also plot the realized gain in dBic, as can be appreciated by those in the art. The elevation cut patterns are a $\cos^n$ two petal rose and the two radiation pattern lobes are oriented broadside the loop plane. The half power beamwidth of those lobes is 98

10 degrees and the beams are symmetric in shape. The FIG. 5B azimuth cut in the loop plane is circular. So the antenna **12** has omnidirectional radiation about the horizon when the antenna plane is horizontal. The FIG. 5B plot uses a fine scale of 1/10 decibel per division to show that the azimuth plane pattern ripple is low, about ± 0.25 decibel, and the highly circular azimuth pattern may for instance benefit radio

15 location systems. The antenna **12** has no sidelobes. The gain at pattern peak is 3.6 dBic and this is 1.5 db more than a half wave dipole turnstile (US Patent 1,892,221, to Runge) provides. Polarization in the 5B-5D example was circular broadside to the loop plane and linear in the loop plane. When the loop electrical conductor **13** plane is horizontal the polarization there is horizontal. As background, polarization is the

20 orientation of the E field vector of the far field radio wave.

If a large plane reflector (not shown) is spaced one quarter wavelength ($\lambda/4$) from the antenna **12** a single radiation pattern lobe is formed with 82 degrees beamwidth. When efficiently matched and tuned, the realized gain is 8.2 dBic. If a plane reflector is spaced relatively close to the antenna **12** a "patch antenna" may be

25 formed.

The degree of polarization circularity produced by the FIG. 1 embodiment antenna **12** is extremely high and is nearly ideal. Axial ratios of 0.9999 and higher (perfect circular polarization axial ratio equals one) are achievable from the antenna **12** as the four coupling points **14a**, **14b**, **14c**, **14d** together enforce the

30 loop current distribution. High axial ratio polarization circularity, from the present

invention, may benefit say air traffic radar in looking through rain clutter as rain clutter reflections are known to return circular polarization in the opposite sense, and aircraft tend to be rather random scatterers of polarization.

FIG. 6 depicts the voltage standing wave ratio (VSWR) response of a 1 meter circumference thin wire antenna **12** at each coupling point **14a**, **14b**, **14c**, **14d**. FIG. 6 is normalized to 70 ohms and as can be appreciated the VSWR is less than 1.1 to 1. So, the antenna **12** is advantageously suited for use with coaxial cables. The VSWR response is quadratic (single tuned), the 2 to 1 VSWR bandwidth at each coupling point **14a**, **14b**, **14c**, **14d** is 10.7 percent, and the 6 to 1 VSWR bandwidth is 30.1 percent. The 3 dB gain bandwidth of the antenna **12** may be also be 30.1 percent since a 6 to 1 VSWR may correspond to 3 dB mismatch loss. FIG. 7 plots the driving point impedance at each of the four coupling points **14a**, **14b**, **14c**, **14d** in Smith Chart format. For a thin wire loop electrical conductor **13** of wire diameter of $\lambda/1000$ the loop circumference is 1.05λ at resonance. The normalizing impedance in FIG. 7 was 70 ohms. As those in the art may appreciate the four delay lines **16a**, **16b**, **16c**, **16d** may preferentially have a characteristic impedance of 70 ohms in practice.

The FIG. 1 embodiment may of course provide elliptical polarization if unequal power divisions are provided at the coupling points **14a'**, **14b'**, **14c'**, **14d'**.

Fewer than four or more than four coupling points **14** may be used in antenna **12** but the combination of a loop electrical conductor **13** circumference near one wavelength with four equally spaced coupling points **14** is very effective.

Now described with reference to FIG. 2 is an additional embodiment, wherein the antenna **12'** is configured for operation using simultaneous right hand and left hand circular polarization. The antenna **12** may provide polarization duplexing with high isolation between the opposite polarization senses.

Here, a quadrature hybrid unit **26'** drives the antenna **12'** at the coupling points **14a'**, **14b'**, **14c'**, **14d'**, providing 0 and 90 degree phasing at its outputs. In addition, here, there are two antenna feeds **18a'**, **18b'**, each of which feeds a power divider **22'**, **24'**, respectively. The power dividers are each coupled to two opposite coupling points (i.e., **14a'** and **14c'**, and **14b'** and **14d'**) by respective

delay lines (i.e., **16a'** and **16c'**, **16b'** and **16d'**). Here, the delay lines **16a'**, **16b'**, **16c'**, **16d'** are configured to provide phase delays of 0°, 90°, 180°, and 270°, respectively.

As explained, this design provides for transmission or reception of dual
5 circularly polarized signals, allowing for simultaneous transmission of two separate signals. In addition, this design may be used for full duplex communications, where a transmitter may simultaneously be operated at coupling points **14a'** and **14c'**, and a receiver at coupling points **14b'** and **14d'**, without mutual interference.

This antenna **12'** provides a very high axial ratio which may approach
10 1.0. Such a high axial ratio means that there is little to no interference of the right hand circularly polarized signal caused by the left hand circularly polarized signal, or vice versa. This is highly desirable in satellite communications, for example for frequency reuse. In addition, this embodiment may be advantageous at high (HF) frequencies for NVIS (near vertical incidence skywave) communications.

With reference to FIG. 3, a version of the antenna **32** that is configured
15 for linear polarization operation rather than circular polarization is now described. This antenna **32** is similar to the antenna **12** described with reference to FIG. 1, but the delay lines **36a**, **36b**, **36c**, **36d** are sized differently. Here, the delay lines **36a**, **36b**, **36c**, **36d** are sized such that the phases at the coupling points **34a**, **34b**, **34c**, **34d**
20 are -180°, 0°, 0°, and 180°, respectively.

This phase configuration results in linear polarization, rather than
circular polarization. In particular, this antenna **32** produces horizontal linear
polarization into and out of the page. If the phases at the coupling points were **34a**,
34b, **34c**, **34d** reversed, the antenna **32** would produce vertical linear polarization into
25 the page.

The radiation patterns for the FIG. 3 embodiment are similar to those
of FIG. 5A-5C, except that that the loop plane null is deeper. Simulations have shown
the gain there to be to -54 dBic and the null may be infinitely deep in theory.
Reduced loop plane radiation may be advantageous to avoid interference to terrestrial

communications when the antenna **32** is pointed overhead. The antenna **32** may have a standing wave current distribution.

Now, an embodiment of the antenna **30'** that is configured for simultaneous operation using both horizontal and linear polarization, e.g., dual linear polarization or duplexed linear polarization is described with reference to FIG. 4. In this embodiment, there are two antenna feeds **38a'**, **38b'** carrying a signal to be transmitted or received using vertical polarization, and a signal to be transmitted or received using horizontal polarization, respectively. The antenna feed **38a'** is coupled to two delay lines **36b'**, **36d'**, while the antenna feed **38b'** is coupled to the two delay lines **36a'**, **36c'**. The delay lines are sized such that the phases at the coupling points **34a'**, **34b'**, **34c'**, **34d'** are -180° , 0° , 0° , and 180° , respectively, thereby providing simultaneous horizontal and vertical polarization.

The ability to operate using both horizontal and vertical polarization simultaneously can provide polarization diversity, and may have the effect of producing greater penetration into buildings and difficult reception areas than a signal with just one plane of polarization. In the antenna **30'**, the vertical polarized coupling points **34a'**, **34c'** and horizontal polarized coupling points **34b'**, **34d'** are isolated from one another, and may also be used as independent communication channels, or for duplex communications. For instance, a transmitter may be included at one of the signal feedpoints, and a receiver used at the other.

The embodiments of the present inventions are not so limited as to require gaps in the loop electrical conductor **13** to form the coupling points **14a**, **14b**, **14c**, **14d**. Other approaches may be utilized such as gamma matches, Y matches, or delta matches as are common for dipole and yagi-uda antenna driven elements. In this regard, the textbook "Antennas For All Applications", John Kraus, Ronald J. Marhefka, 3rd edition, Tata McGraw-Hill, 2002 is identified as a reference in its entirety and the Figure 23-19 page 822 is referenced in specific.

Table 1 provides a comparison between the antenna **12** and the circularly polarized half wave dipole turnstile antenna:

Table 1 Comparison Of The Antenna 12 With The Dipole Turnstile		
Parameter	Antenna 12, Circularly Polarized Loop	½ Wave Dipole Turnstile
Physical dimensions	0.33λ circle	0.34λ by 0.34λ square (dipoles run from corner to corner)
Subtended area	$0.08\lambda^2$	$0.12\lambda^2$
Wire diameter	$\lambda/1000$	$\lambda/1000$
Realized gain	3.6 dBic	2.1 dBic
Half power beamwidth	98 degrees	126 by 172 degrees
Port impedances	$70 + j0$	$72 + j0$
2 to 1 VSWR bandwidth, each port	10.7 percent	11.2 percent
3 dB gain bandwidth	30.1 percent	33.7 percent
Polarization	Circular	Circular

A full wave circularly polarized loop antenna 12 therefore provides many advantages over the prior art half wave dipole turnstile: more gain, a symmetric beam, reduced size. The bandwidth for size is greater with the loop 12. The antenna 12 provides
5 circular polarization of exceptional circularity: unlike the turnstile it is not easily upset by tolerances. So, the antenna 12 may replace the turnstile in many applications such as satellite communications and ionospheric communications.

Referring now to FIGS. 8 and 9, in another embodiment, the wireless communications device 110 includes a waveguide transducer 112. The waveguide
10 transducer 112 may be in the form of a circular waveguide, for example. This embodiment may be particularly well suited for feeding conical horns for increased

directivity and gain, and it may excite conical horns in the dominant TE_{11} mode for circular polarization. The waveguide transducer **112** includes a loop electrical conductor **113** having a two spaced apart gaps therein defining a two respective spaced apart coupling points **114a**, **114b**. The two spaced apart coupling points **114a**, **114b** are separated by one quarter of a length of the loop electrical conductor **113**. The length of the loop electrical conductor corresponds to an operating wavelength of the waveguide transducer. Of course, in some embodiments, the coupling points **114a**, **114b** may have a different spacing, and the loop electrical conductor **113** may have a different circumference. A larger circumference loop electrical conductor **113** may excite higher order waveguide modes, if desired.

The feed assembly includes two waveguide feeds **118a**, **118b**, or feed points, and a feed network in the form of two delay lines **116a**, **116b** coupled between the two waveguide feeds, and the two coupling points **114a**, **114b**. In other embodiments, the feed network may alternatively or additionally include digital delay processing circuitry configured to provide a delay. In other words, the digital delay processing circuitry may execute computer-executable instructions to provide phase delays. Since there are two coupling points **114a**, **114b**, and two delay lines **116a**, **116b**, the 180° power dividers are not used.

The waveguide transducer **112** also includes a waveguide **140** surrounding the loop electrical conductor **113**. The loop electrical conductor **113**, two delay lines **116a**, **116b**, the waveguide feeds **118a**, **118b**, and the waveguide **140** advantageously cooperate to function as a waveguide transducer.

The waveguide **140** extends outwardly from the loop electrical conductor **113**, and includes a cylindrical body **141**, having an open end **142** and an opposing closed end **143**. The closed end **143** carries the loop electrical conductor **113**. The body **141** of the waveguide **140** may be another shape.

The reflector **140** may be electrically conductive, for example, and may be metallic. The cylindrically shaped body **141** of the waveguide **140** is sized so that it extends outwardly beyond the loop electrical conductor **113**. In other words,

the loop electrical conductor **113** is carried below the open end **142** of the cylindrically shaped body **141**.

The loop electrical conductor **113** is carried by closed end **143** of cylindrically shaped body **141** in spaced apart relation therefrom. More particularly,
5 the loop electrical conductor **113** is spaced above the closed end **143** by the two delay lines **116a**, **116b**. A typical spacing of the loop electrical conductor **113** above the closed end **143** by a distance of $\lambda_g/4$ or a quarter of a wavelength. The cylindrical body **141** may also be 2λ or two wavelengths long from the closed end **143** to the open end **142**. Of course, the cylindrical body **141** may be another length, and the
10 loop electrical conductor **113** may be spaced differently.

The waveguide transducer **112** also includes a horn **150** coupled to the open end **142** of the waveguide **140**. More particularly, the horn **150** includes a frusto-conical body **151** having a smaller opening **152** coupled to the open end **142** of the waveguide **140** and a larger opening **152** opposing the smaller opening **151**. The
15 horn **150** advantageously focuses RF waves from the loop electrical conductor **113** and provides increased gain. The loop electrical conductor **113** excites the waveguide **140** and the horn **150** in the TE₁₁ mode, which is used for satellite communications, for example.

The horn **150** may further include impedance elements **154** carried by
20 an interior of the conical body **151**. The impedance elements **154** are illustratively in the form of rings defining a choke. The impedance elements **154** cooperate with the frusto-conical body **151** to reduce current on the interior of the frusto-conical body. As will be appreciated by those skilled in the art, current has a tendency to “walk back” along the frusto-conical body **151**.

Referring now to FIG. 10, another embodiment of the waveguide
25 transducer **112'** is illustrated. The feed assembly includes two waveguide feeds **118a'**, **118b** coupled between the quadrature power divider **126'** and the 180° power dividers **122'**, **124'**. The loop electrical conductor **113'** has four spaced apart gaps therein defining a plurality of four respective spaced apart coupling points **114a'**,
30 **114b'**, **114c'**, **114d'**. The feed network is in the form of four delay lines **116a'**,

116b', **116c'**, **116d'**, as described above, and further includes digital delay processing circuitry **146'**. Each delay line **116a'**, **116b'**, **116c'**, **116d'** is coupled between the waveguide feeds **118a'**, **118b'** and a respective one of the four coupling points **114a'**, **114b'**, **114c'**, **114d'**. The four spaced apart coupling points **114a'**, **114b'**, **114c'**, **114d'** are separated by one quarter of a length of the loop electrical conductor **113'**. The length of the loop electrical conductor **113'** corresponds to an operating wavelength of waveguide transducer **112'**.

The digital delay processing circuitry **146'** may execute computer-executable instructions and cooperate with the delay lines to provide phase delays of 0° , 90° , 180° , 270° , respectively. In some embodiments, the digital delay processing circuitry **146'** may be used without the four delay lines **116a'**, **116b'**, **116c'**, **116d'**. The digital delay processing circuitry **146'** may also be configured to perform additional functions, for example, that of the power dividers **122'**, **124'**, **126'**.

Referring now to FIGS. 11 and 12, a Smith Chart of simulated driving point impedance **170'** for the waveguide transducer **112'** and simulated voltage standing wave ratio (VSWR) are illustrated, respectively. Cusp **171'** corresponds to the TE₁₁ waveguide mode, the cusp **172'** corresponds to the TM₀₁ mode, and the cusp **173'** corresponds to the TE₂₁ mode (FIG. 12). As illustrated in the graphs, the waveguide transducer **112'** tunes and matches to about 50 Ohms. The first resonance occurred at a loop circumference of 0.86 free space wavelengths, e.g., $0.86\lambda_{\text{free space}}$. Without the waveguide transducer **112'**, the loop electrical conductor **113'** would have had first resonance at about $1.05\lambda_{\text{free space}}$. The graph in FIG. 12 is a VSWR response for operation in a 50 ohm system, so a 50 ohm antenna corresponds to a 1 to 1 VSWR, a 100 ohm antenna impedance corresponds to a 2 to 1 VSWR, etc.

Referring now to FIG. 13a, a waveguide transducer **112'** without the horn **150'** in a radiation pattern coordinating system is illustrated, and FIGS. 13b-13d, simulated radiation patterns for a waveguide transducer **112'** without the horn **150'** are illustrated. In other words, the radiation patterns are for an open ended waveguide having the loop electrical conductor **113'** inside. FIG. 13a illustrates the waveguide transducer **112'** in an industry standard (IEEE-145) radiation pattern coordinate

system with the radiated beam oriented along the Z axis. The graph in FIG. 13b illustrates the simulated radiation pattern cut taken in the XZ plane. The graph in FIG. 13c illustrates the simulated radiation pattern cut taken in the YZ plane, and the graph in FIG. 13d illustrates the simulated radiation pattern taken in the X-Y plane.

- 5 The illustrated radiation patterns are advantageously a rotationally symmetric pattern corresponding to a $\cos^n$ shape, which may be particularly suited to exciting conical horns and parabolic reflectors, for example.

Referring to the graphs in FIGS. 14a-14c, the field rotation of waveguide transducer **112'** in the TE₁₁ mode is illustrated. A cross section of a portion of the waveguide **140'** along with the loop electrical conductor **113'** is illustrated in FIGS 14a-14c. FIG. 14a illustrates a rotation of 0°. FIG. 14b illustrates, at a later time, a phase rotation of 50°, and FIG. 14c illustrates a phase rotation of 90° at an even later time. The contours **182'** represent constant E field amplitude. As illustrated, the field rotation angularly rotates at $\omega = 2\pi f$, which advantageously provides circular rotation.

Referring now to the graph in FIG. 15, the simulated axial ratio for the waveguide transducer **112'** is illustrated. The line **176'** illustrates a relatively high axial ratio, thus rejecting left-hand circular polarization. Opposite sense polarization is down 52dB. Performance specifications for the waveguide transducer **112'** based upon simulations are highlighted below in Table 2, where λ_{fs} are wavelengths in free space.

Parameter	Value
Device	Waveguide transducer having circular loop probe, quadrature excitation
Application	Suitable to conical horn feed
Ring Transducer, Major Circumference Of Toroid	$0.86\lambda_{fs}$
Ring Transducer, Outside Diameter	$0.460\lambda_{fs}$
Ring Transducer, Minor Diameter Of Toroid	$0.186\lambda_{fs}$

Ring Transducer, Centerline Height Above End Wall	$0.316\lambda_{fs}$
Ring Transducer, Centerline Height Above End Wall	$0.316\lambda_{fs}$
Waveguide Type	Circular
Waveguide, Inside Diameter	$0.593\lambda_{fs}$
Waveguide, Inside Circumference	$1.863\lambda_{fs}$
Waveguide, Length	$3.16\lambda_{fs}$
Realized Waveguide Mode	TE ₁₁
Number Of Ring Ports	4, as fine gaps
Port Types	50 ohm coaxial
Port Impedance	$Z=46-j5\ \Omega$
VSWR (50 Ω system)	1.14:1
Loop Excitation	Quadrature
Polarization	Circular
Gain (open ended waveguide, no horn, splash plate etc.)	4.36_dBic
3 db Beamwidth (open ended waveguide, no horn, splash plate etc.)	124°
Polarization	Circular
Polarization Ratio	52dB (high circularity, opposite sense down 52 dB)

Table 2

A method aspect is directed to a method of making a waveguide transducer **112** for use in a wireless communications device **110**. The method

5 includes forming a loop electrical conductor **113** having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points **114a**, **114b**, and forming a feed assembly by forming a feed network **116a**, **116b** and coupling the feed network between the waveguide feeds **118a**, **118b** and the plurality of coupling points **114a**, **114b**. The method also includes positioning a waveguide

10 **140** to surround the loop electrical conductor **113** and extend outwardly therefrom. The waveguide **140** includes a tubular body **141** having an open end **142** and an opposing closed end **143** carrying the loop electrical conductor **113**.

The embodiments described herein may provide a circular waveguide transducer for the TE₁₁ and other waveguide modes, and a coax to waveguide transition. A circular loop electric conductor may generate electromagnetic fields and may provide one or more of linear polarization, circular polarization, and dual
5 polarization. The embodiments, including the waveguide transducer **112** may simplify reflector antenna feeds by reducing rectangular waveguide components, such as, for example, the magic T hybrid and rectangular to circular waveguide transducers.

Additional details of a wireless communications device including a
10 related antenna may be found in related application attorney docket Nos. GCSD-2490 and GCSD-2491, and U.S. Patent Application Publication No. 2008/0136720 to Parsche et al, all of which are assigned to the present assignee, and the entire contents of each of which are herein incorporated by reference. Many modifications and other
15 embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

CLAIMS

1. A wireless communications device comprising:
wireless communications circuitry; and
5 a waveguide transducer coupled to said wireless communications circuitry and comprising
a loop electrical conductor having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points,
10 a feed assembly comprising
at least one waveguide feed, and
a feed network coupled between said at least one waveguide feed and said plurality of coupling points, and
a waveguide surrounding said loop electrical conductor and
15 extending outwardly therefrom, and comprising a tubular body having an open end and an opposing closed end carrying said loop electrical conductor.
2. The wireless communications device of Claim 1, wherein said
20 tubular body comprises a cylindrically shaped body.
3. The wireless communications device of Claim 1, wherein said waveguide transducer further comprises a horn coupled to the open end of said waveguide.
25
4. The wireless communications device of Claim 3, wherein said horn comprises a frusto-conical body having a smaller opening coupled to the open end of said waveguide and a larger opening opposing the smaller opening.

5. The wireless communications device of Claim 4, wherein said horn further comprises a plurality of impedance elements carried by an interior of said frusto-conical body.

5 6. A method of making a waveguide transducer for use in a wireless communications device comprising:
forming a loop electrical conductor having a plurality of spaced apart gaps therein defining a plurality of respective spaced apart coupling points;
forming a feed assembly by forming a feed network and coupling the
10 feed network at least one waveguide feed and the plurality of coupling points; and
positioning a waveguide to surround the loop electrical conductor and extend outwardly therefrom, and comprising a tubular body having an open end and an opposing closed end carrying the loop electrical conductor.

15 7. The method of Claim 6, wherein positioning the waveguide comprising a tubular body comprises positioning a waveguide comprising a cylindrically shaped body.

8. The method of Claim 6, further comprising coupling a horn to
20 the open end of the waveguide.

9. The method of Claim 8, wherein coupling the horn comprises coupling a horn comprising a frusto-conical body having a smaller opening coupled to the open end of the waveguide and a larger opening opposing the smaller opening.

25 10. The method of Claim 9, wherein coupling the horn comprises coupling a horn comprising a plurality of impedance elements carried by an interior of the frusto-conical body.

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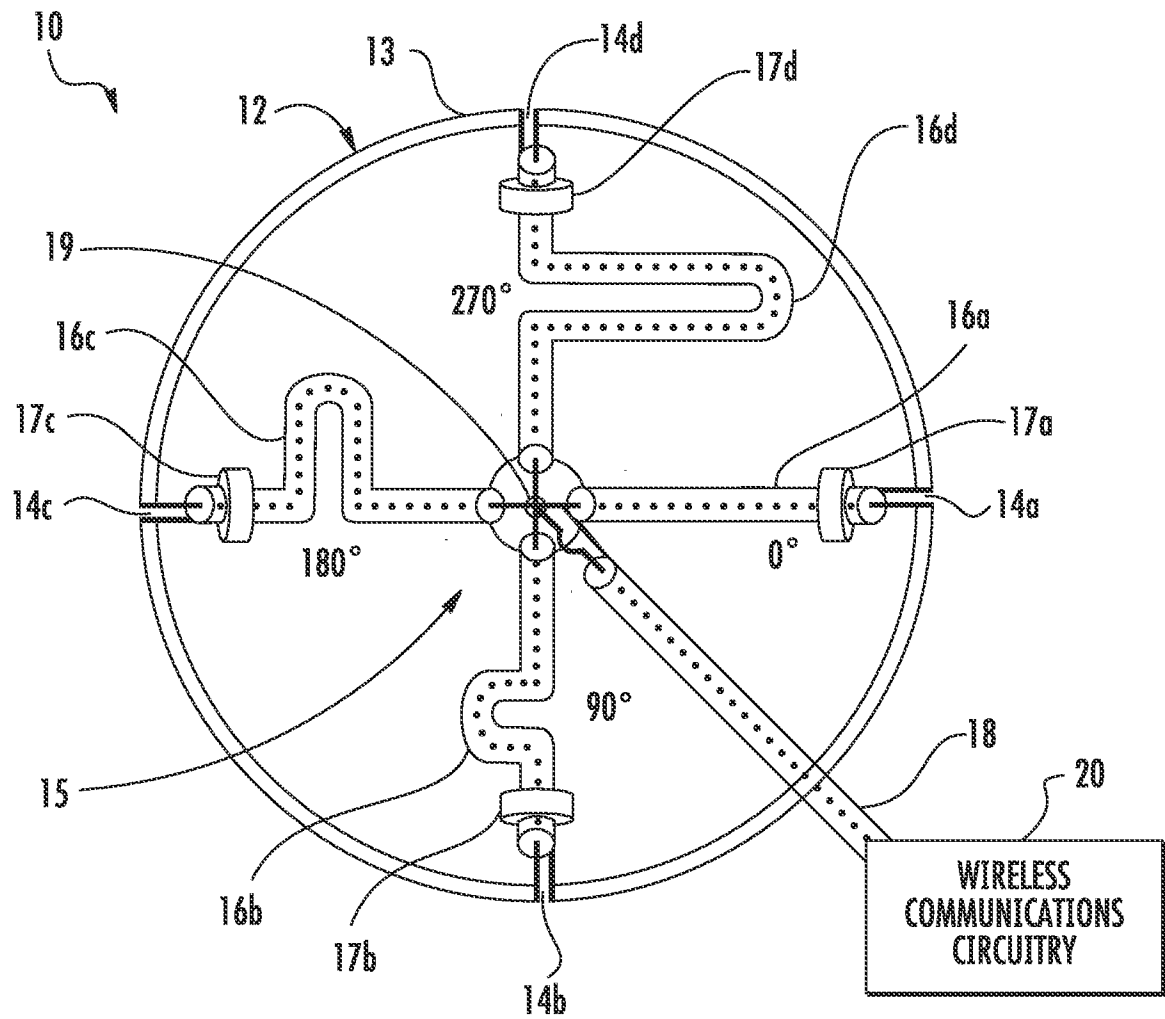


FIG. 1

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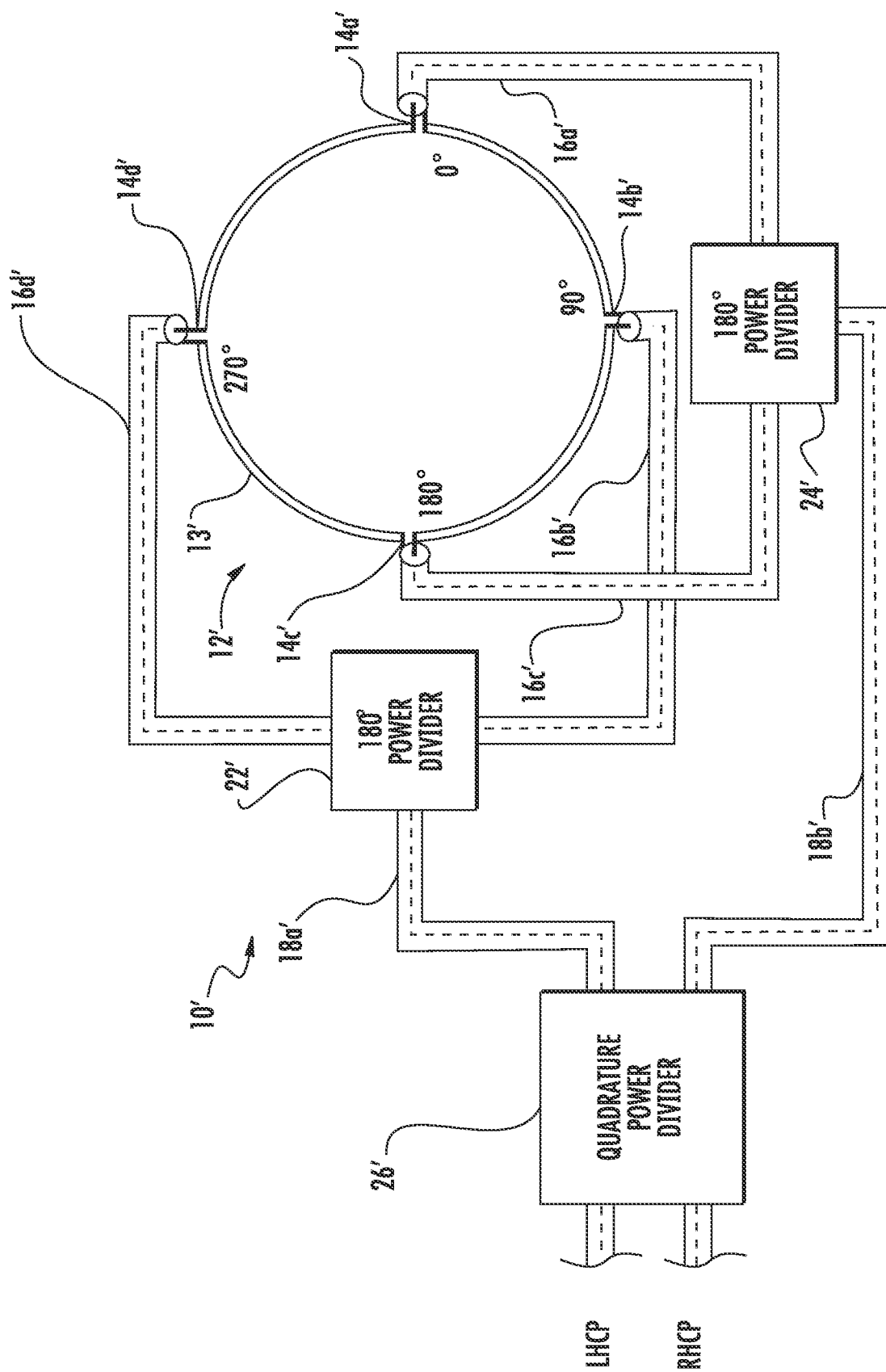


FIG. 2

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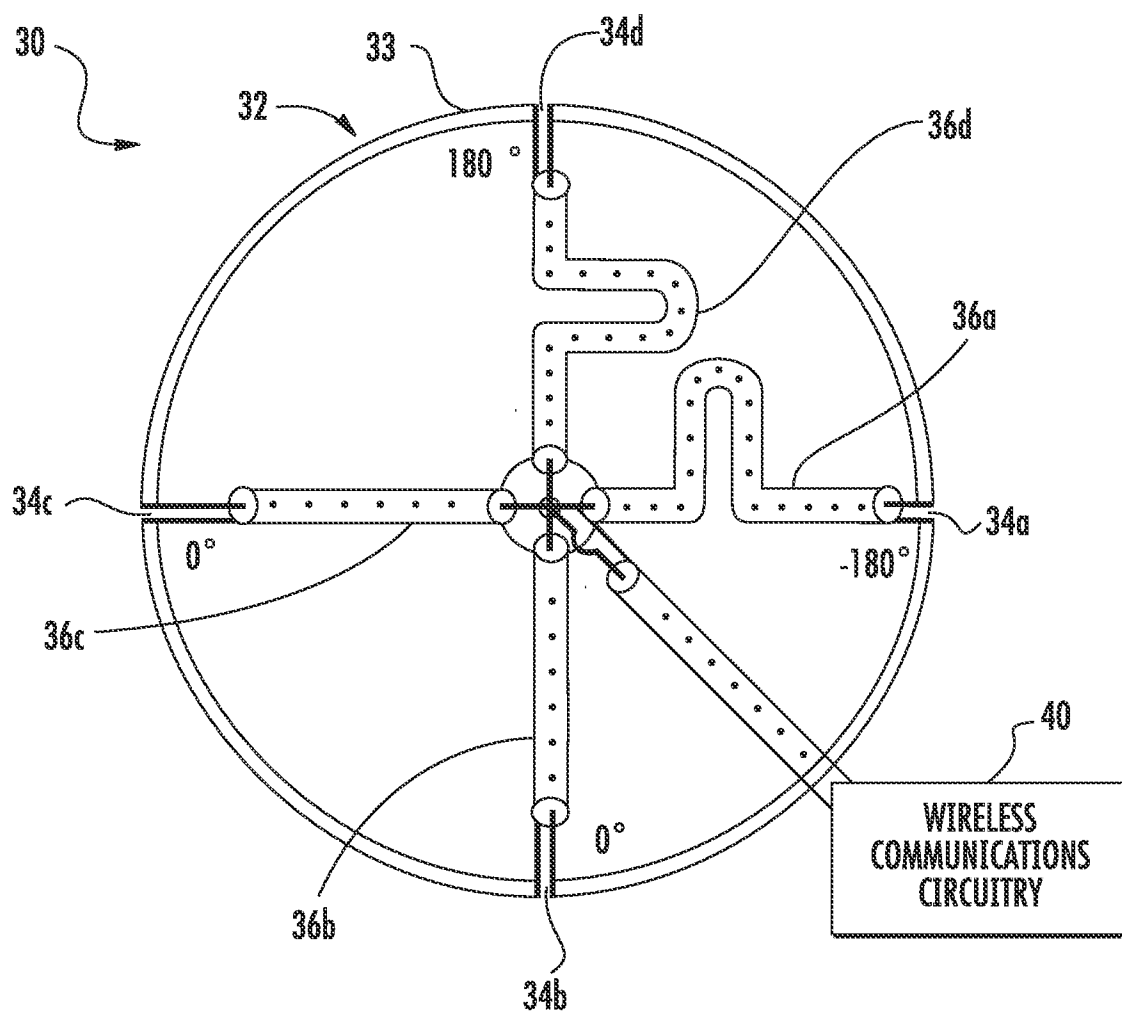


FIG. 3

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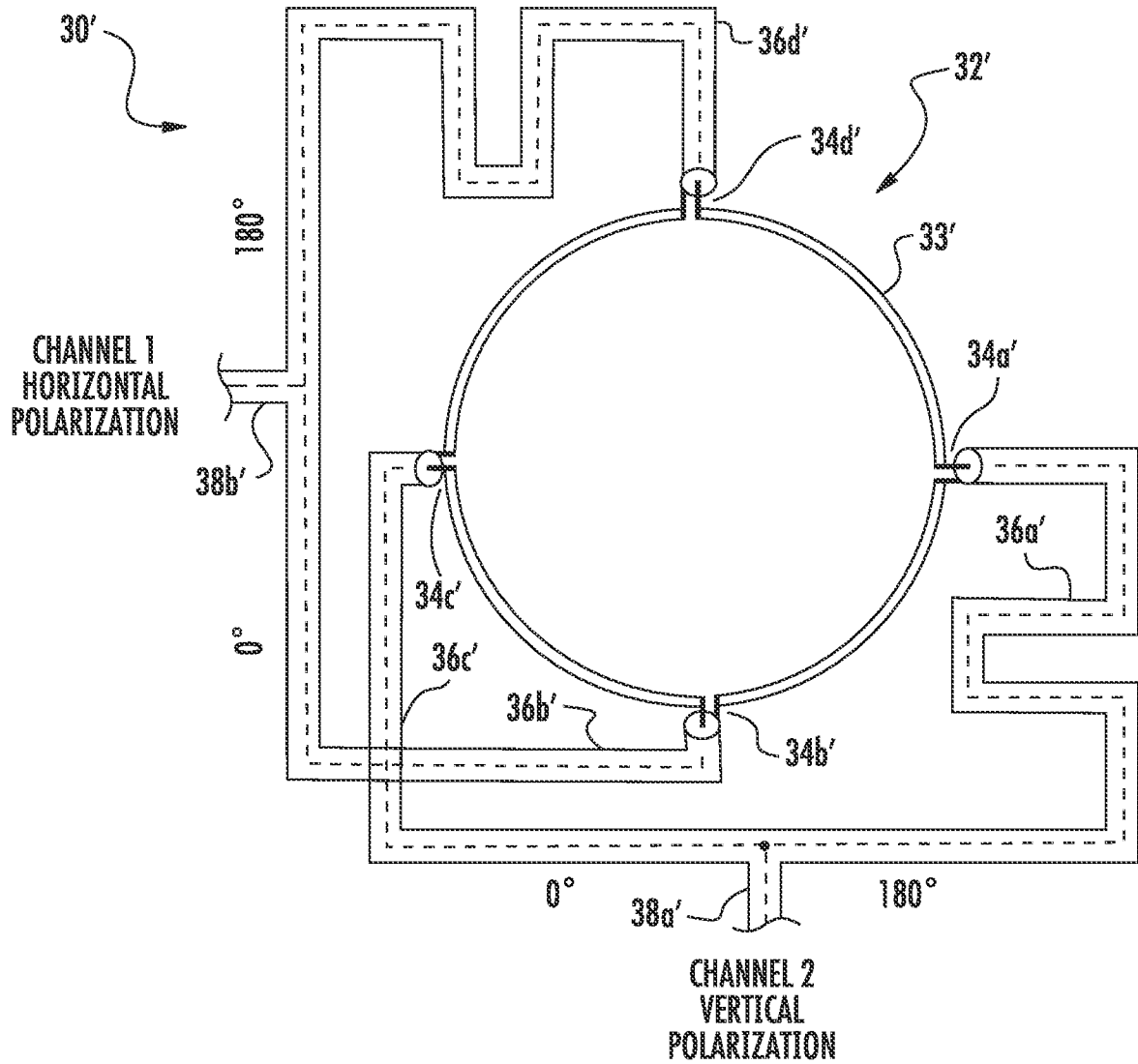
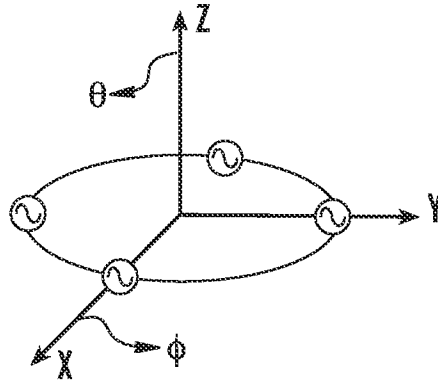
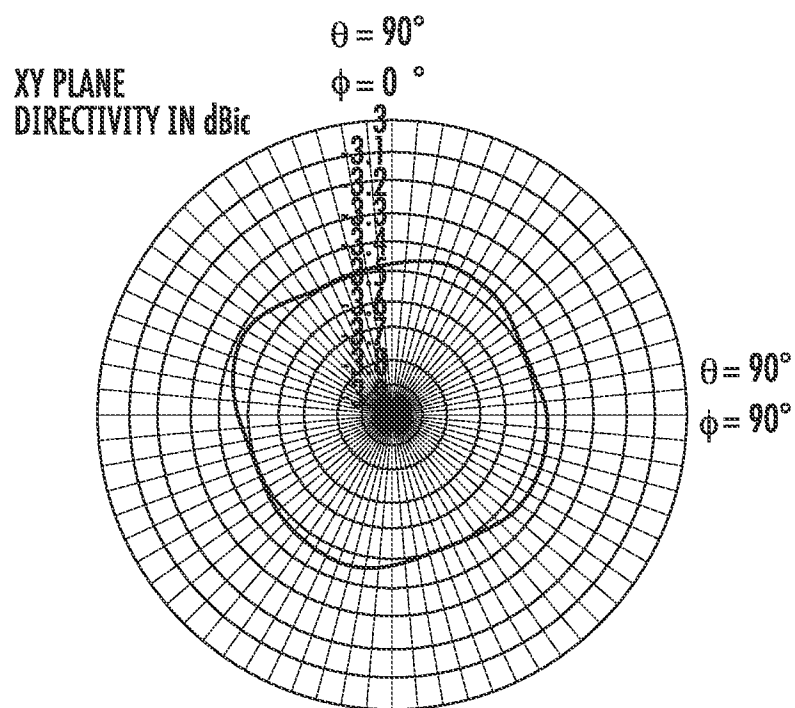


FIG. 4

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**FIG. 5A****FIG. 5B**

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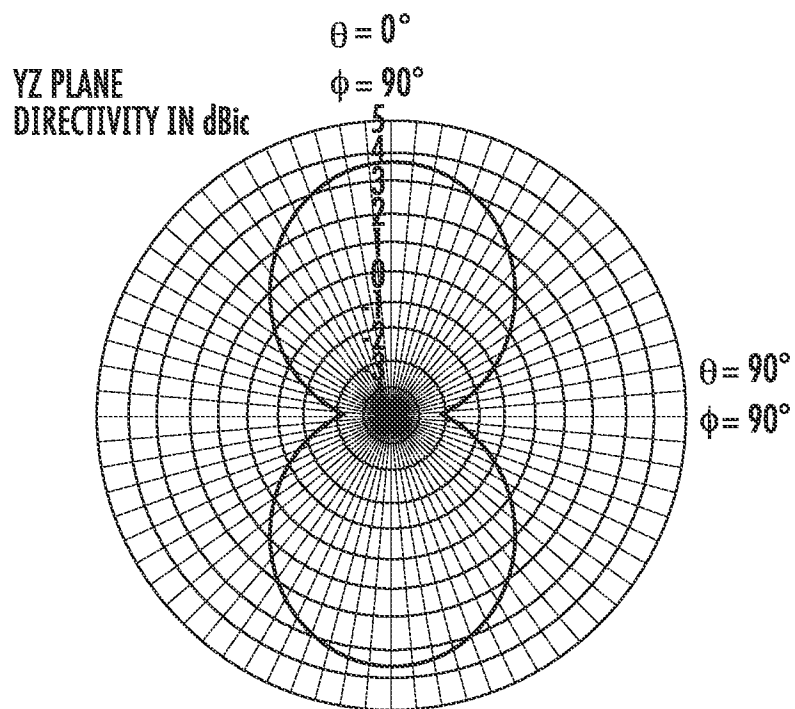


FIG. 5C

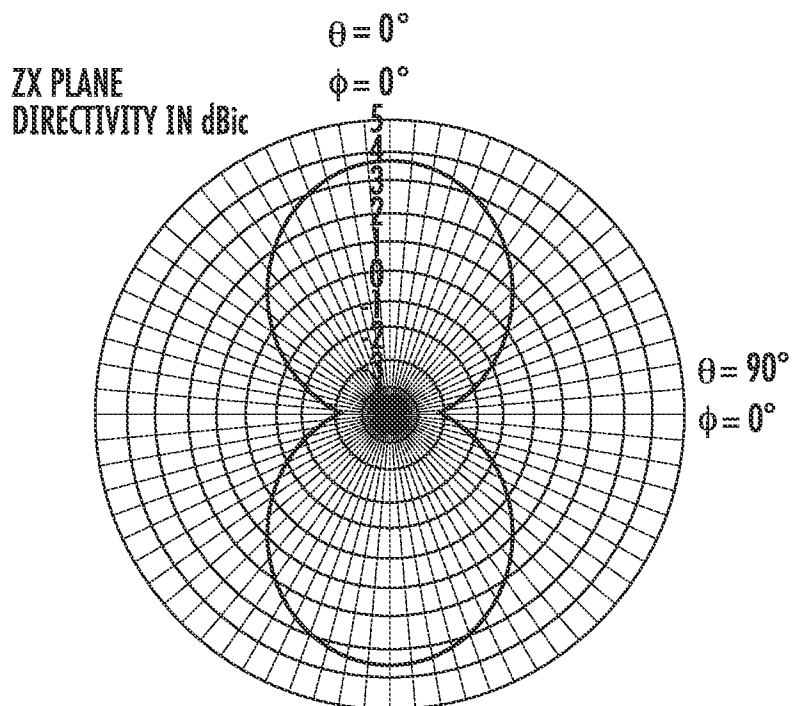


FIG. 5D

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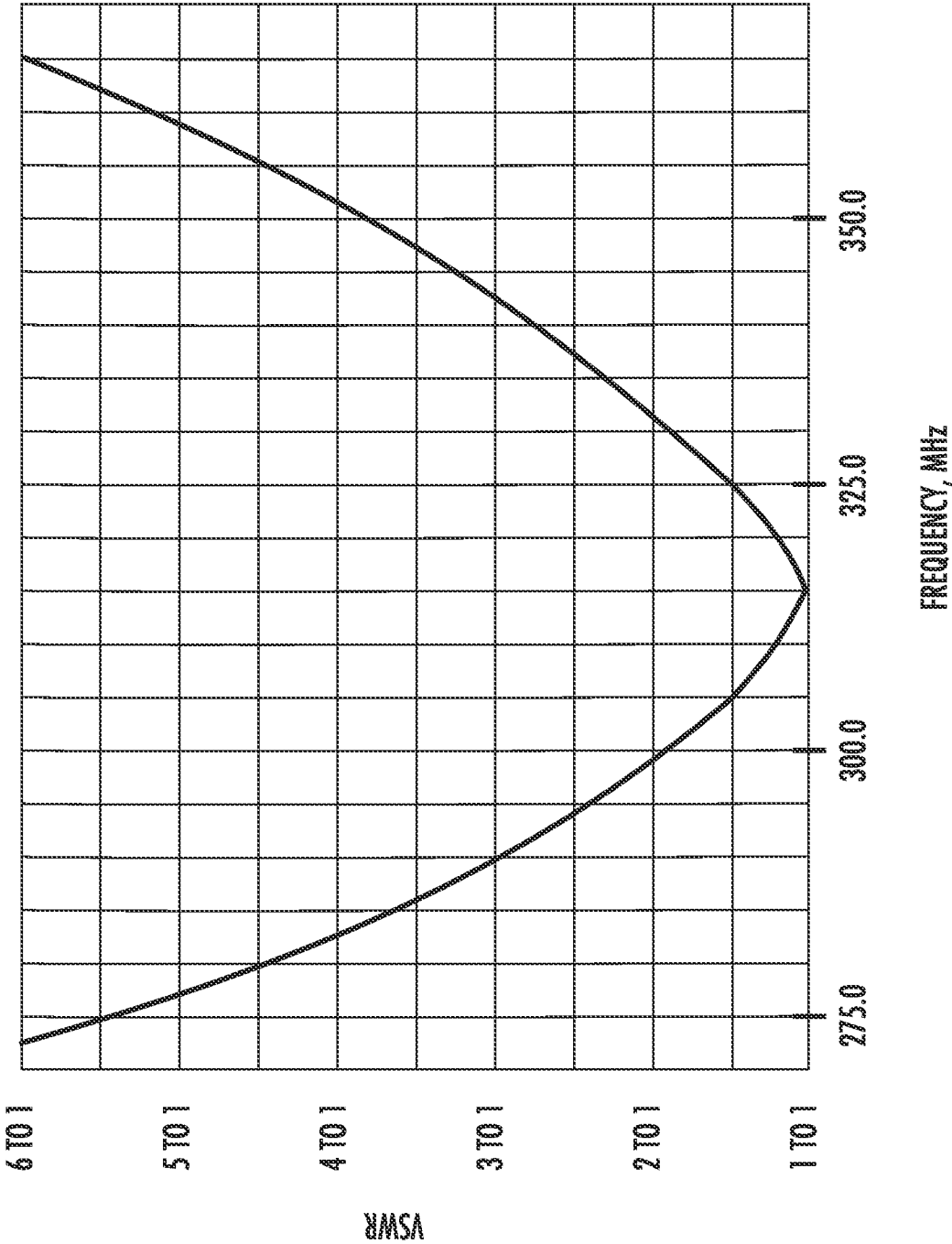


FIG. 6

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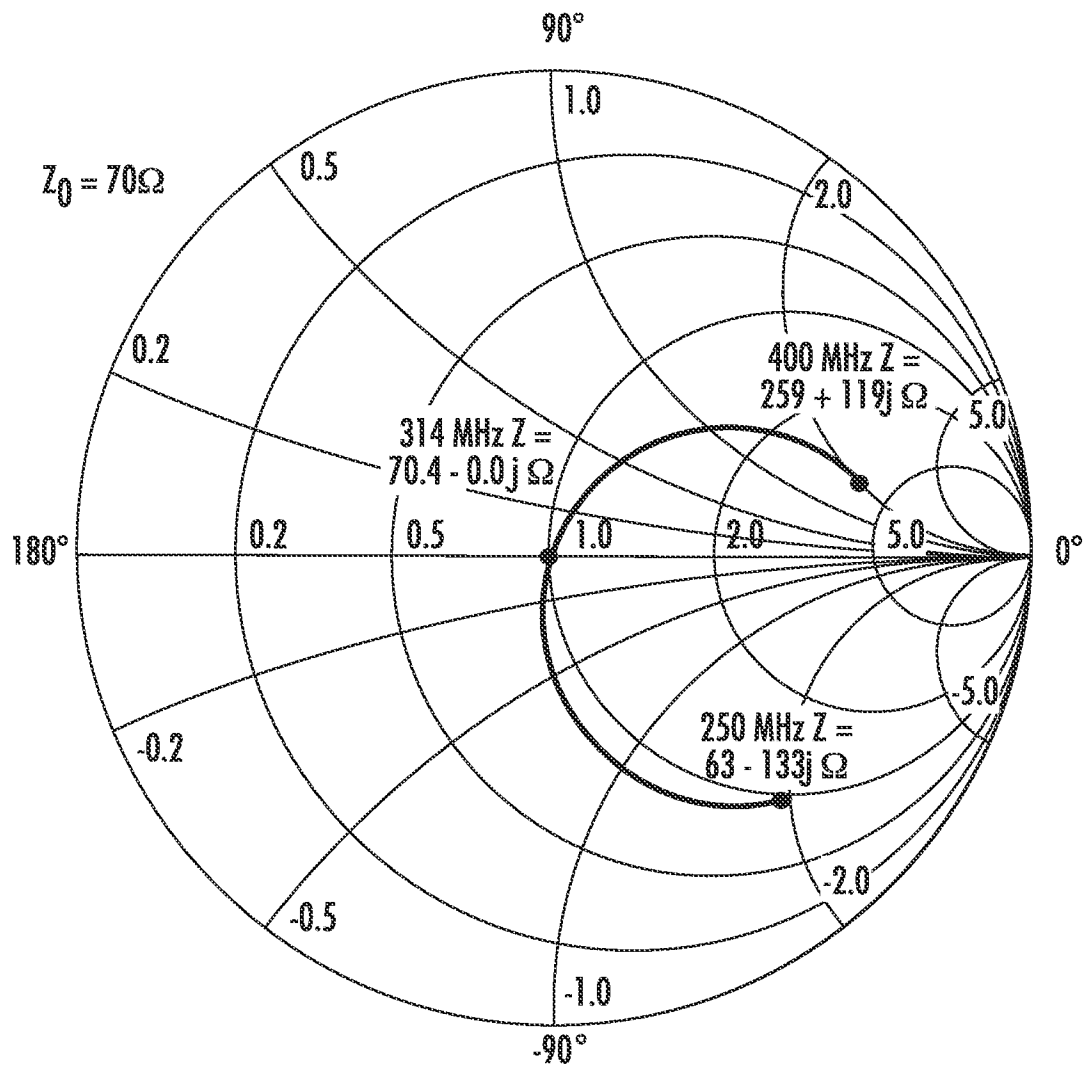


FIG. 7

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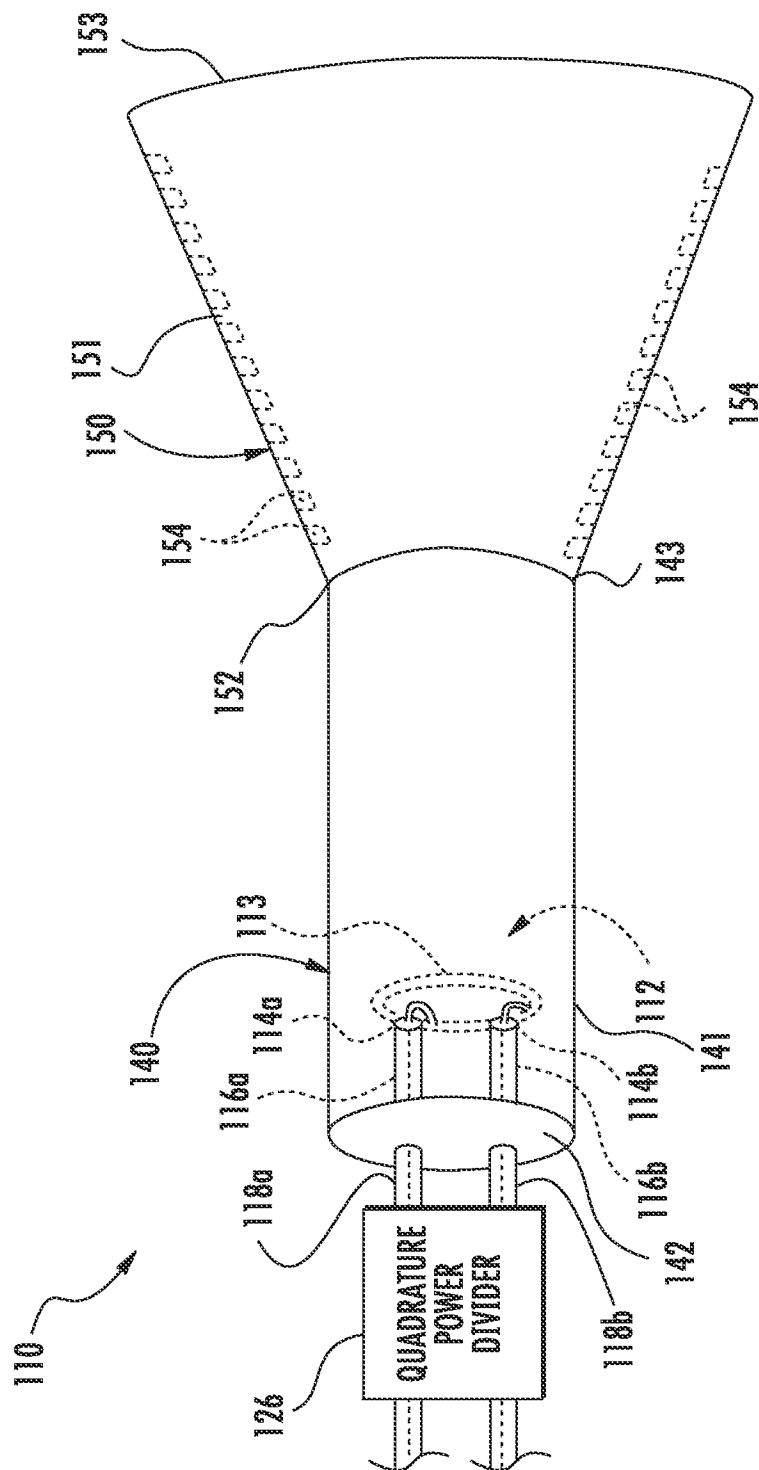


FIG. 8

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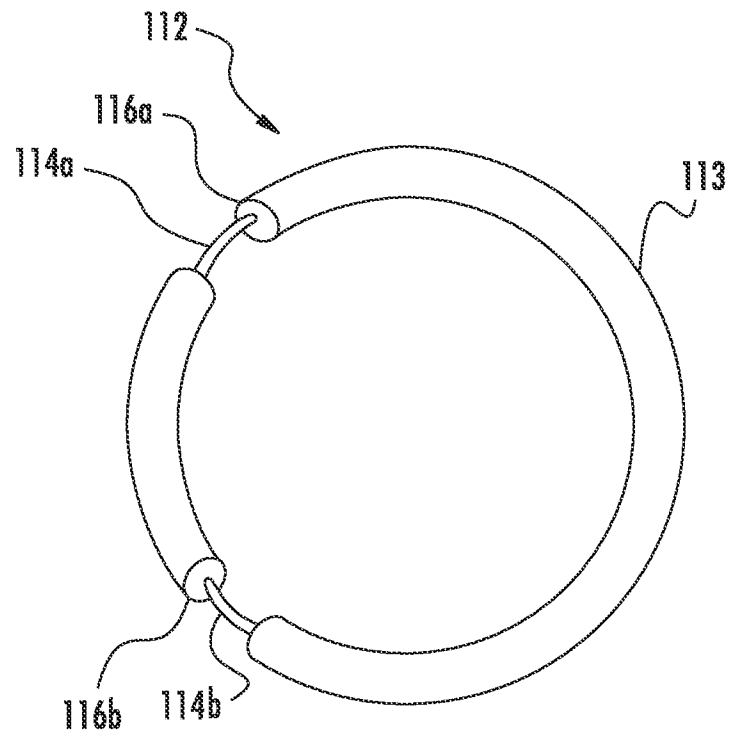


FIG. 9

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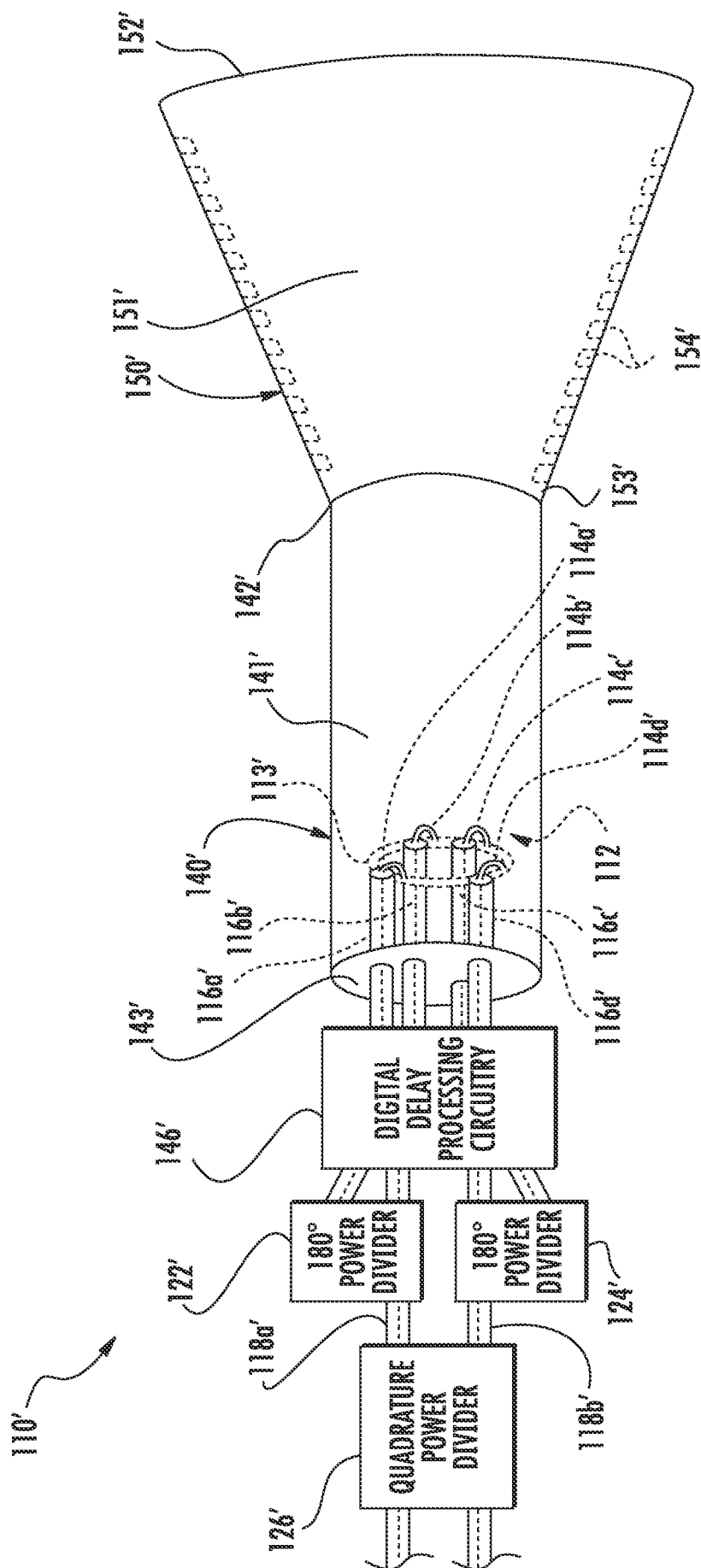


FIG. 10

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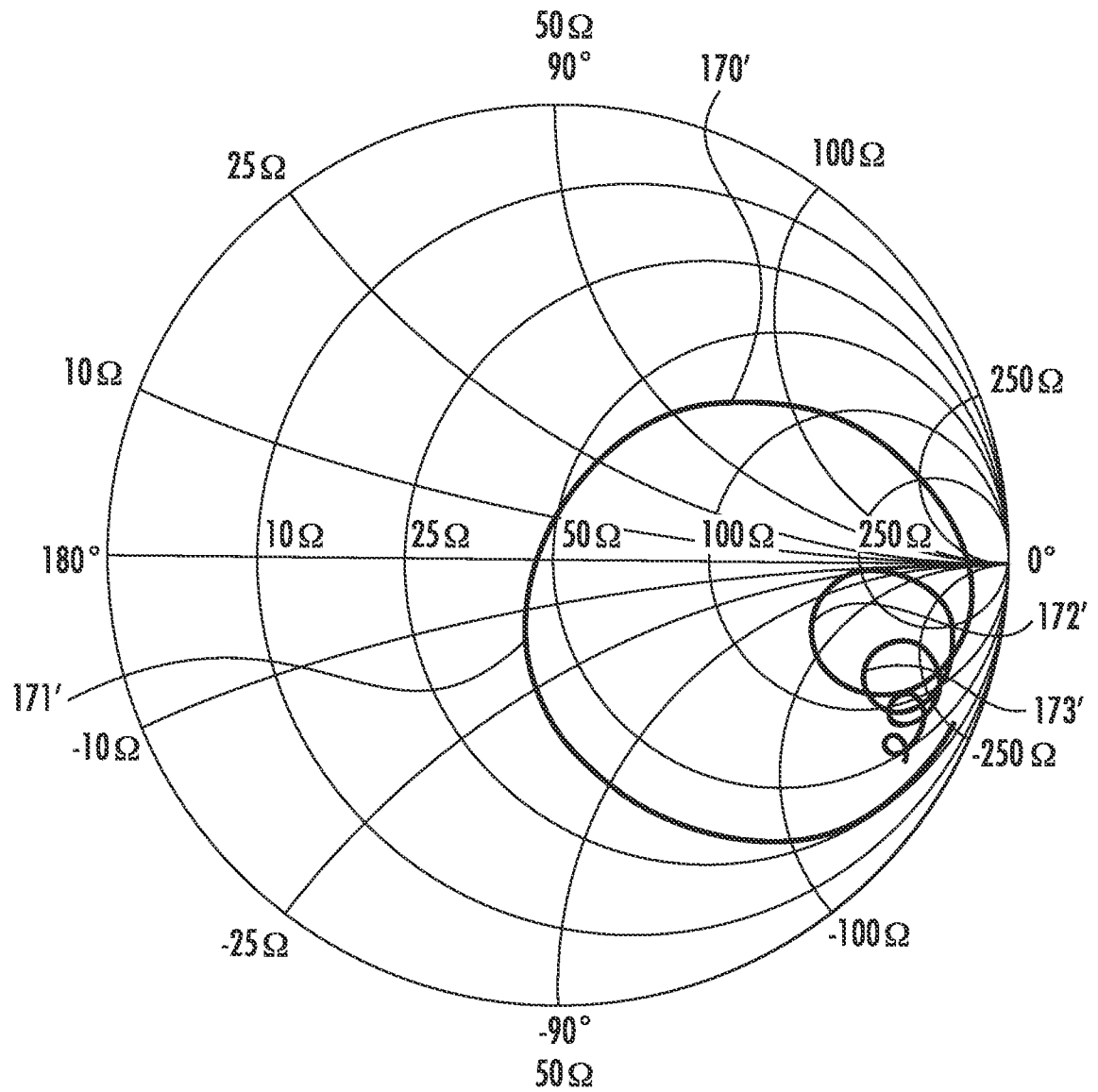


FIG. 11

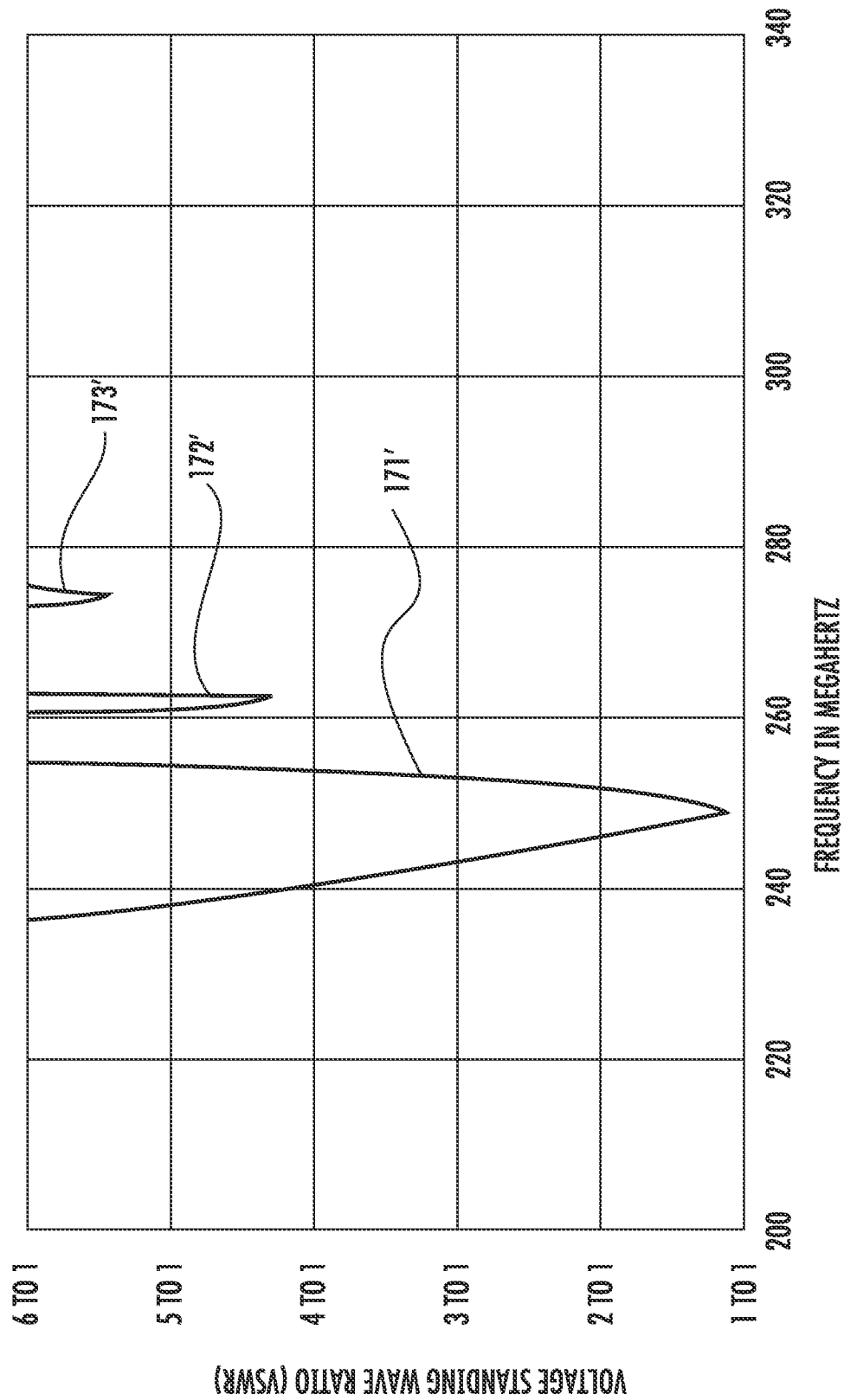
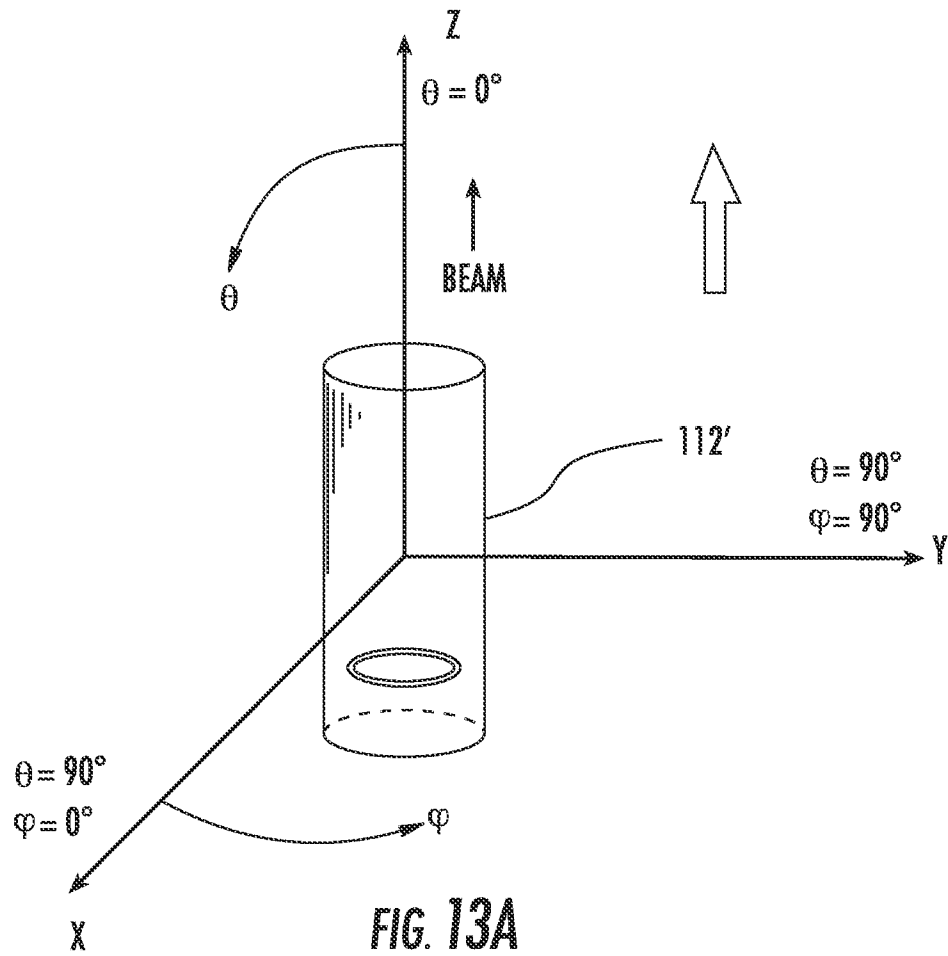


FIG. 12

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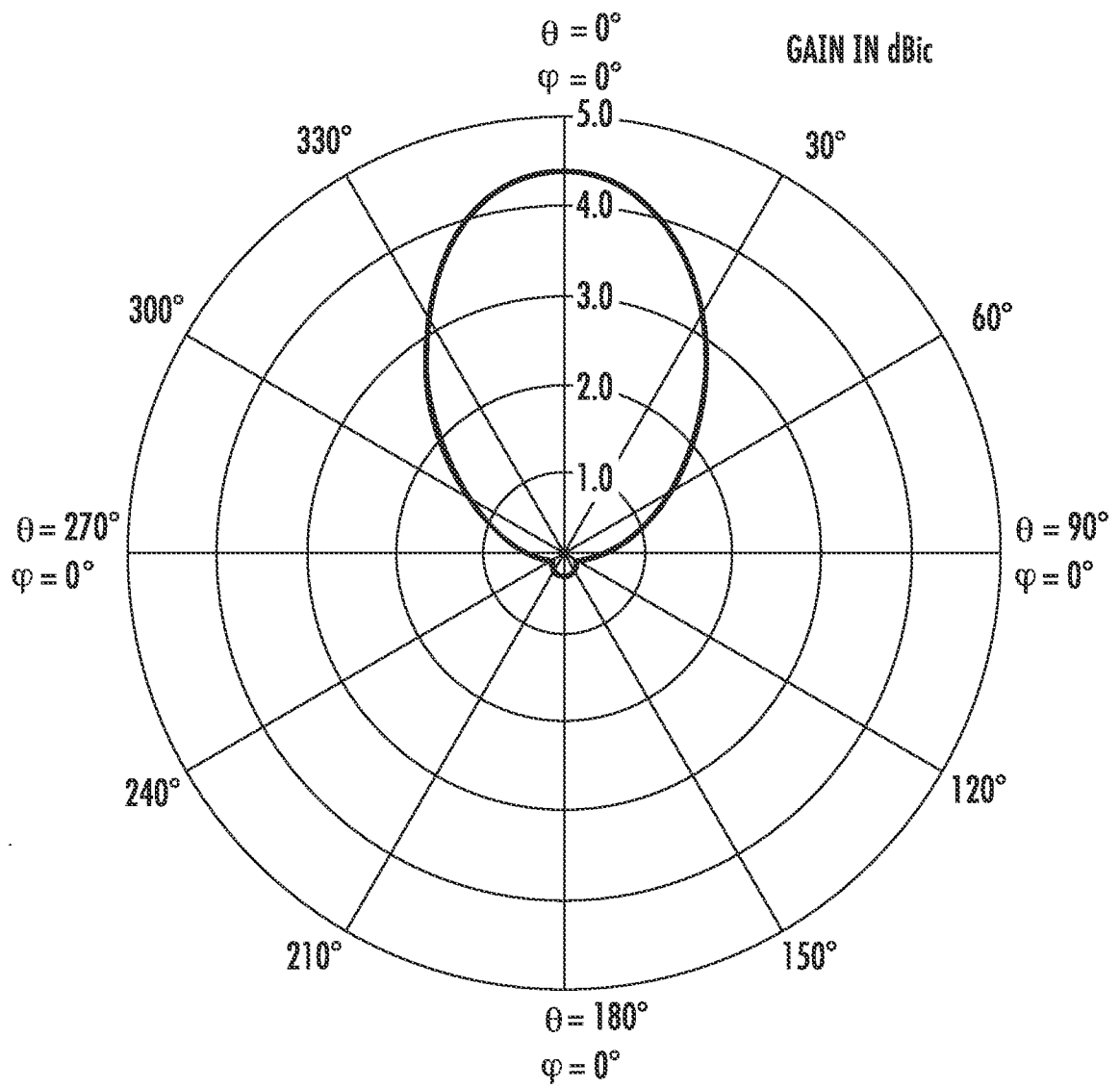


FIG. 13B

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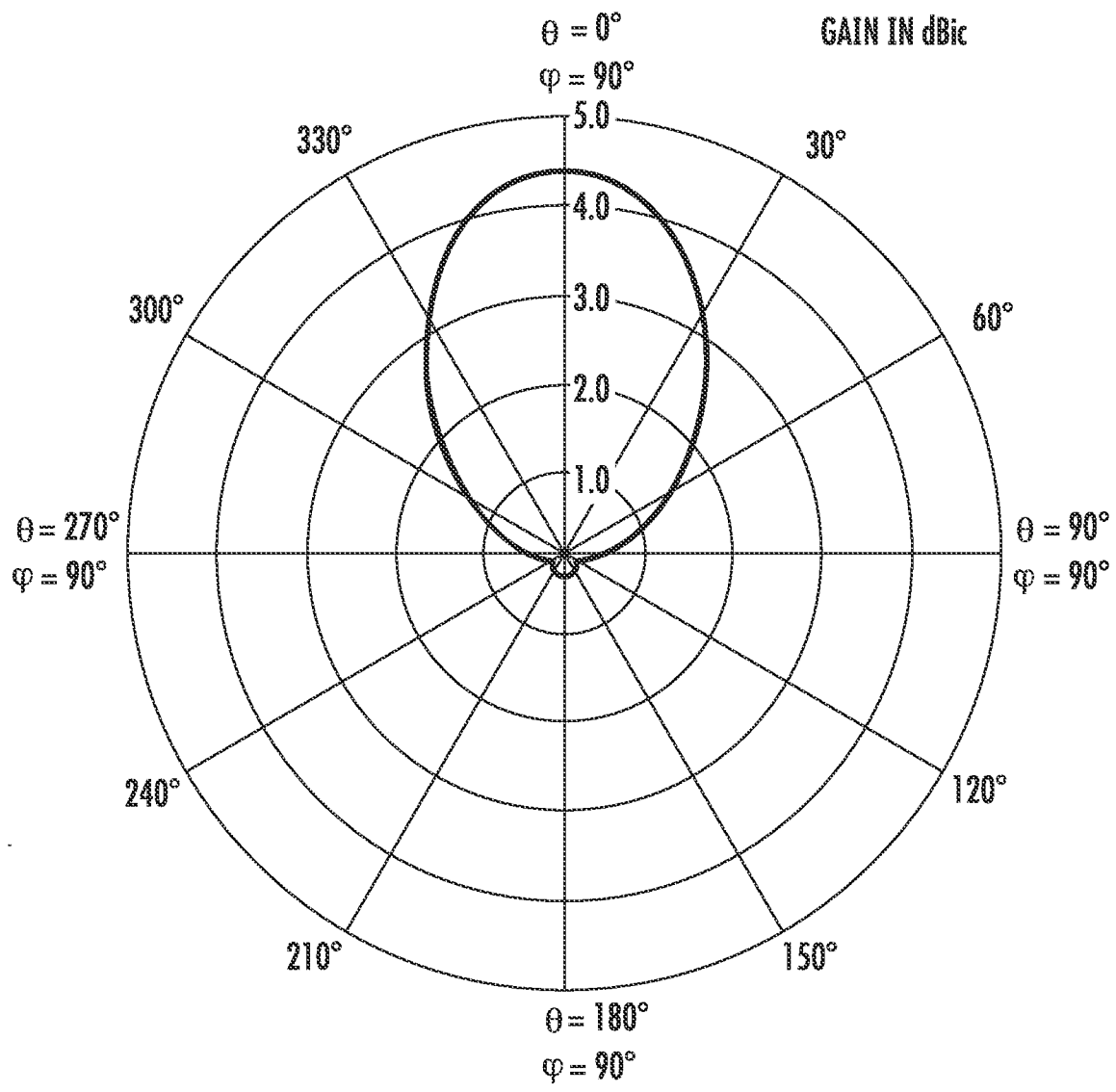
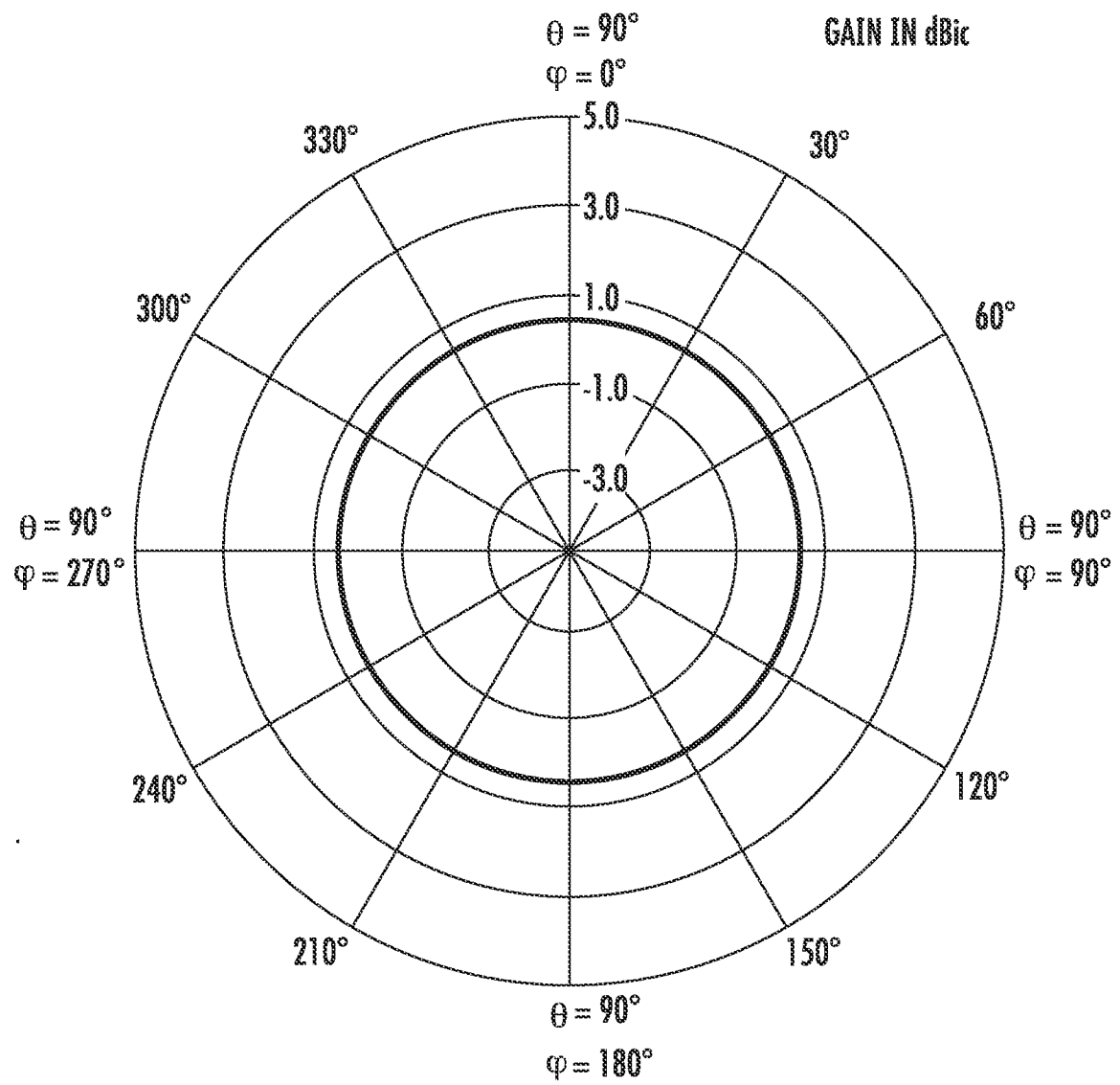
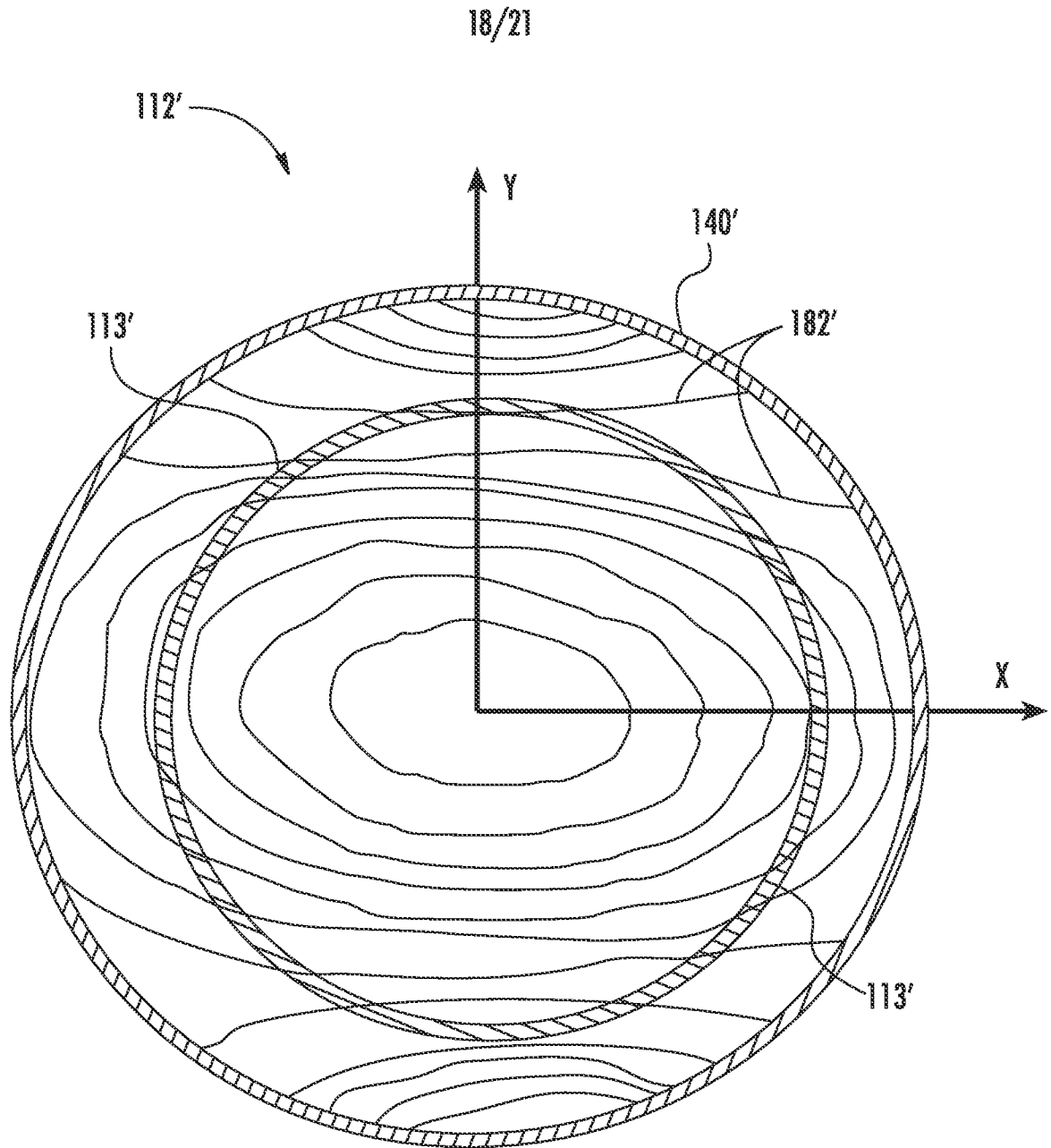


FIG. 13C

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**FIG. 13D**

**FIG. 14A**

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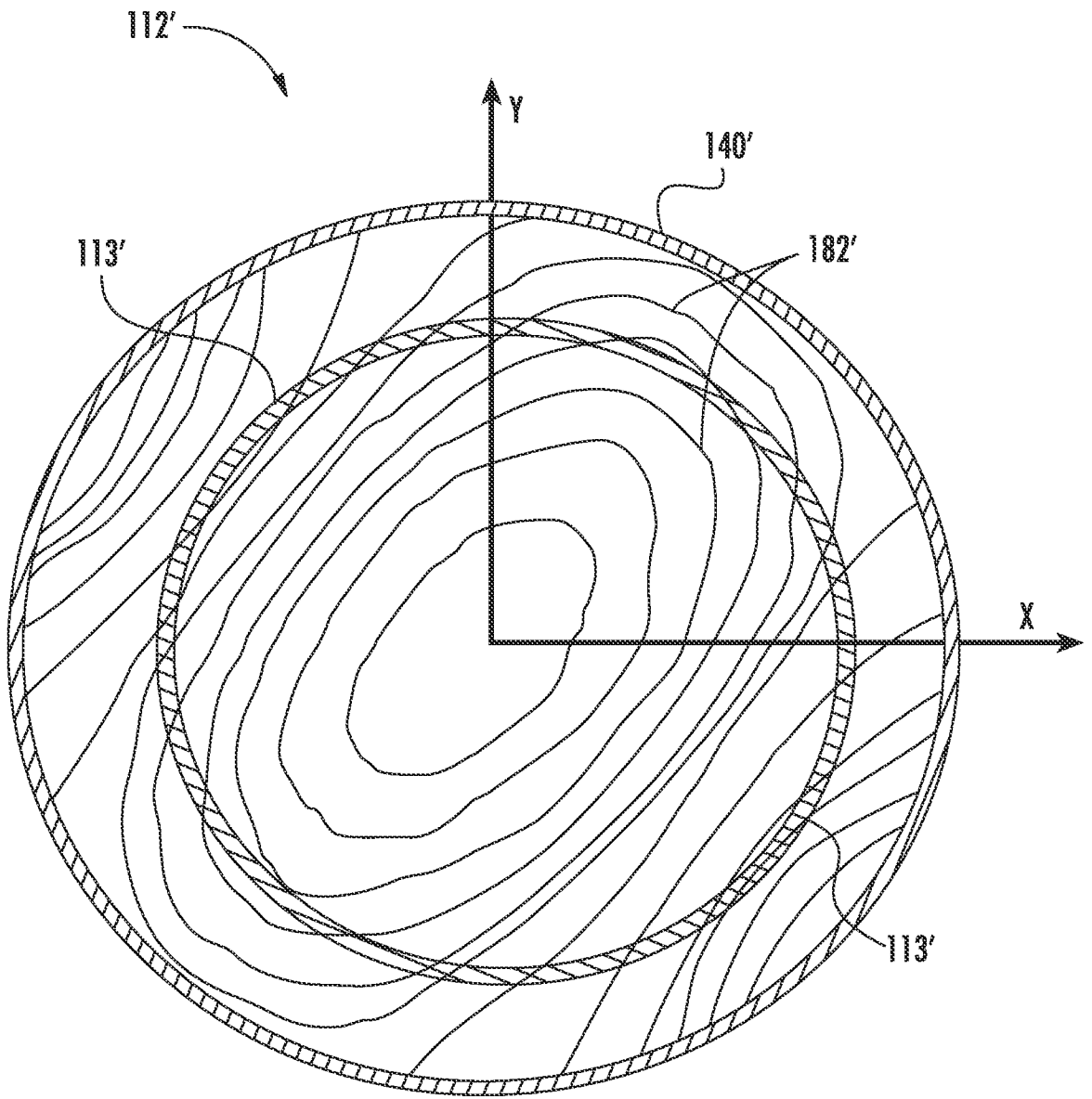


FIG. 14B

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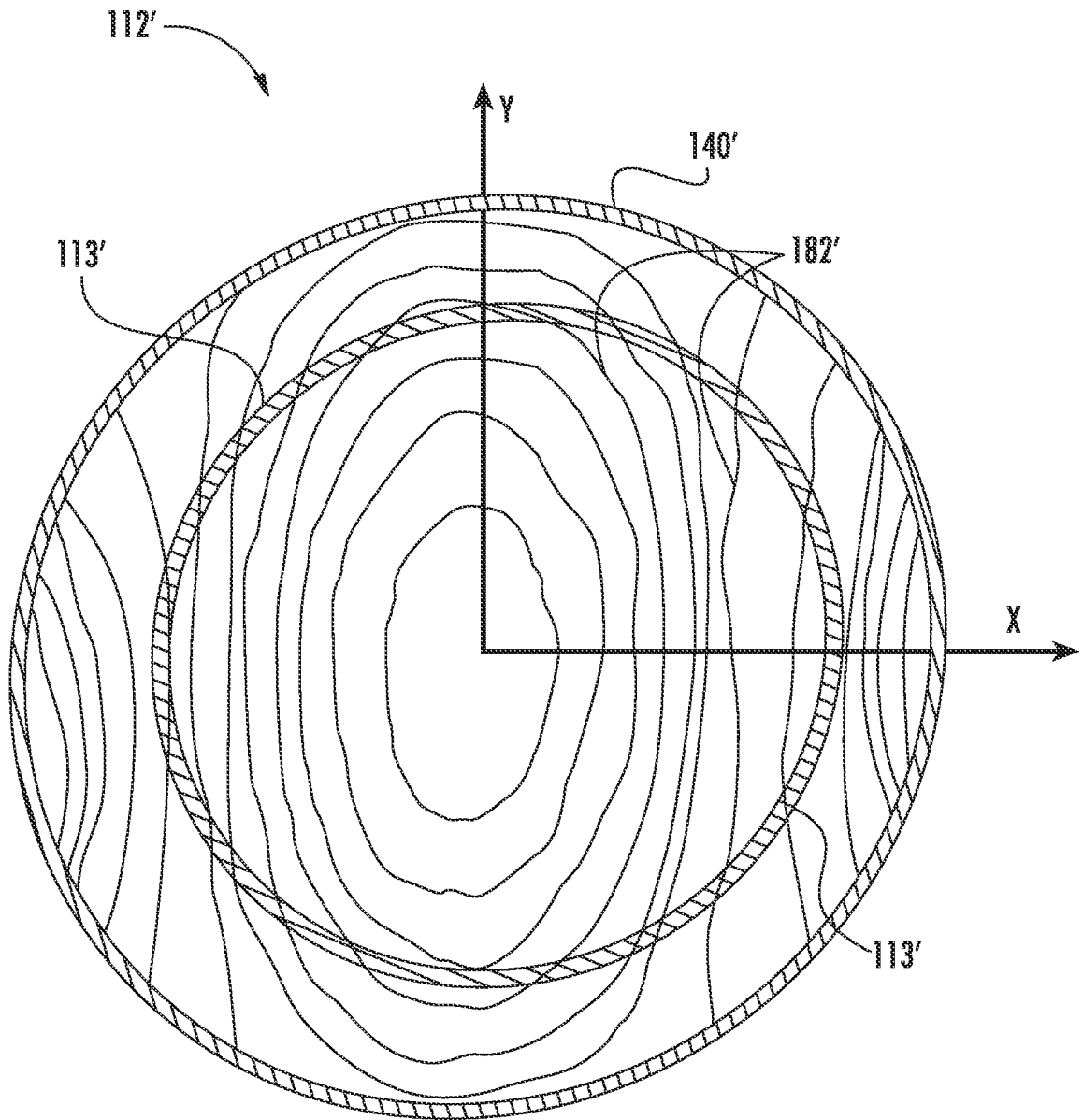


FIG. 14C

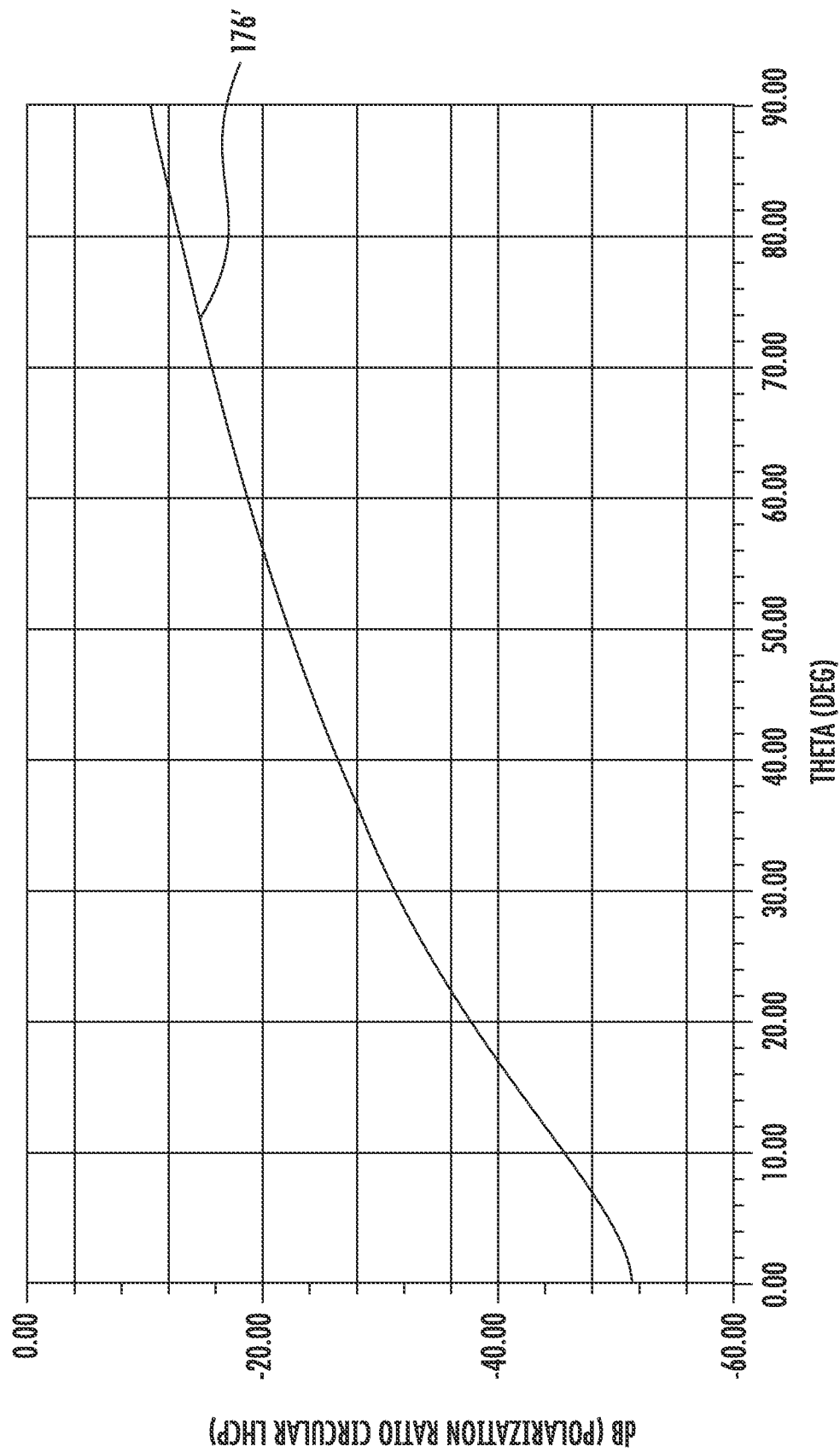


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/023698

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01Q7/00 H01Q13/02 H01Q19/13
ADD.

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)
H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 03 110904 A (YOKOWO CO LTD) 10 May 1991 (1991-05-10)	1,2,6,7
Y	the whole document	3-5,8-10
X	US 6 078 297 A (KORMANYOS BRIAN K [US]) 20 June 2000 (2000-06-20) abstract	1,2,6,7
Y	US 2005/088355 A1 (KRALOVEC JAY A [US] ET AL) 28 April 2005 (2005-04-28) figure 2	3-5,8-10
	----- -/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

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"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

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"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

24 April 2013

Date of mailing of the international search report

03/05/2013

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
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Wattiaux, Véronique

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2013/023698

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	NORROD R D ET AL: "DESIGN AND IMPLEMENTATION OF A LOW-NOISE PRIME-FOCUS S/X RECEIVER SYSTEM FOR RADIO ASTRONOMY", PROCEEDINGS OF THE IEEE, IEEE. NEW YORK, US, vol. 82, no. 5, 1 May 1994 (1994-05-01), pages 768-775, XP000458785, ISSN: 0018-9219, DOI: 10.1109/5.284744 figure 3	3-5,8-10
A	----- US 3 358 287 A (HELMUT BRUECKMANN) 12 December 1967 (1967-12-12) figure 4	1-10
A	----- US 2008/136720 A1 (PARSCHE FRANCIS EUGENE [US] ET AL) 12 June 2008 (2008-06-12) cited in the application the whole document -----	1-10

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2013/023698

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US 2005088355	A1	28-04-2005	NONE	
US 3358287	A	12-12-1967	NONE	
US 2008136720	A1	12-06-2008	NONE	