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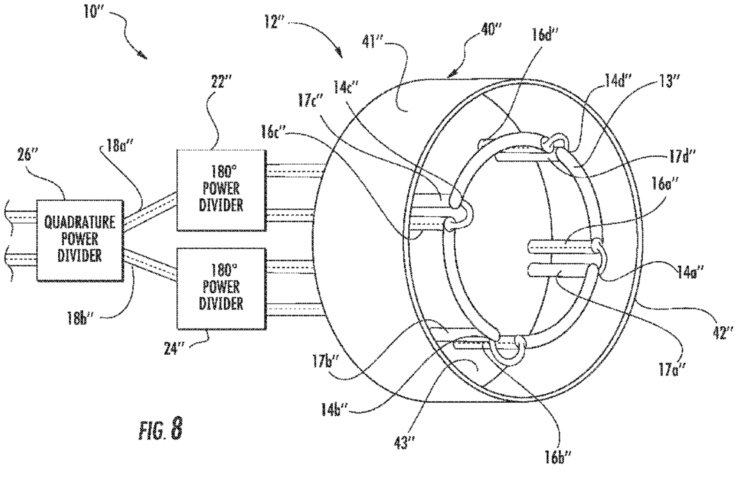

FIG. 8

(57) **Abstract**: A wireless communications device may include wireless communications circuitry and an antenna coupled to the wireless communications circuitry. The antenna may include a loop electrical conductor (13") having four spaced apart gaps therein defining four respective spaced apart coupling points (14a"-d"), and a feed assembly. The feed assembly may include at least one antenna feed, and a feed network coupled between the at least one antenna feed and the four coupling points. The antenna may also include a reflector (40") surrounding the loop electrical conductor.

WO 2013/119410 A1

WIRELESS COMMUNICATIONS DEVICE HAVING LOOP ANTENNA WITH FOUR SPACED APART COUPLING POINTS AND REFLECTOR AND ASSOCIATED METHODS

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.

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.

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 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, 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.

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 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 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 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 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 an antenna 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 an antenna coupled to the wireless communications circuitry. The antenna includes a loop electrical conductor having four spaced apart gaps therein defining four respective spaced apart coupling points, and a feed assembly including at least one antenna feed, and a feed network coupled between the at least one antenna feed and the four coupling points. The antenna also includes a reflector surrounding the loop electrical conductor. Accordingly, the antenna allows operation using both linear and circular polarization, for example, and provides robust performance.

The reflector may include a cylindrically shaped body having an open end and an opposing closed end carrying the loop electrical conductor. The antenna may further include at least one passive element carried by the reflector and spaced apart from the loop electrical conductor, for example. The at least one passive element may include a plurality thereof having ring shapes and with circumferences that decrease in size as a distance from the loop electrical conductor increases, for example.

The spaced apart coupling points may be separated by one quarter of a length of the loop electrical conductor. The length of the loop electrical conductor may correspond to an operating wavelength of the antenna.

The feed network may provide phase delays of 0°, 90°, 180°, and 270°, respectively. Alternatively, the feed network may provide phase delays of -180°, 0°, 0°, and 180°, respectively, for example.

The feed network may include digital delay processing circuitry. The feed network may include four delay lines, each delay line coupled between the at least one antenna feed and a respective one of the four coupling points. The at least one antenna feed may include a pair of antenna feeds. The feed assembly may further include a respective power divider coupled to each antenna feed. The delay lines for opposite coupling points may be coupled to a same power divider, and the feed network may provide phase delays of 0°, 90°, 180°, and 270°, respectively, thereby configuring the wireless communications device for circular polarization. Alternatively, the feed network may provide phase delays of -180°, 0°, 0°, and 180°, respectively, thereby configuring the wireless communications device for linear polarization.

A method aspect is directed to a method of making an antenna to be used in a wireless communications device. The method includes forming a loop electrical conductor having four spaced apart gaps therein defining four 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 antenna feed and a respective one of the four coupling points. The method further includes positioning a reflector to surround the loop electrical conductor.

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 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 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.

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 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 wherein the antenna includes a reflector.

FIG. 9 is a graph of VSWR versus frequency for multiple tuning an antenna in accordance with the present invention.

FIG. 10 is a graph of a radiation pattern of the antenna in FIG. 8.

FIG. 11 is a schematic diagram of another embodiment of a wireless communications device in accordance with the present invention wherein the antenna includes four spaced apart loop electrical conductors.

Detailed Description of the Preferred Embodiments

The present invention will now be described more fully hereinafter 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 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, 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 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 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.

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 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 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 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 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 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 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:

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

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 –sine term to the 180 degree excitation at **14c,** and the –cosine 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 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 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 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 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 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 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 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 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 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 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** 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 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', 3bc'**. 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	λ/1000	λ/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 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 FIG. 8, in another embodiment, the antenna **12''** includes a reflector **40''** surrounding the loop electrical conductor **13''**. The reflector **40''** may be electrically conductive, for example, and may be metallic. The reflector **40''** illustratively has a cylindrical shape, and more particularly, a cylindrically shaped body **41''** having an open end **42''** and an opposing closed end **43''**. In other words, the reflector **40''** has the shape of an open cup, for example. The closed end **43''** carries the loop electrical conductor **13''.**

The cylindrically shaped body **41''** of the reflector **40''** is sized so that the loop electrical conductor **13''** does not extend beyond the cylindrically shaped body. In other words, the loop electrical conductor **13''** is carried at or below the open end **42''** of the cylindrically shaped body **41''**.

The loop electrical conductor **13''** is carried by the closed end **43''** of cylindrically shaped body **41''** in spaced apart relation therefrom. More particularly, the loop electrical conductor **13''** is spaced above the closed end **43''** by the feed network **16a''**, **16b''**, **16c''**, **16d''** and corresponding spacers **17a''**, **17b''**, **17c''**, **17d''**. The spacers **17a''**, **17b''**, **17c''**, **17d''** may be a metal tube, for example, and may define an array of baluns, one for each loop driving point. The spacers **17a''**, **17b''**, **17c''**, **17d''** may be about 0.25 wavelengths long at the resonant frequency of the loop electrical conductor **13''** for single tuning of the antenna **12''** loop electrical conductor **13''**In a single tuned antenna **12''** the voltage standing wave ratio (VSWR) response is quadratic near loop electrical conductor **13''** full wave resonant frequency, e.g., there is one VSWR minima.

Referring now additionally to the graph **50''** in FIG. 9, the VSWR for a multiple tuning of the antenna **12''** is illustrated. Multiple resonances **51'', 52''** are configured in the VSWR response **56''** and those multiple resonances **51'', 52''** are staggered in frequency to increase the VSWR bandwidth. The antenna passband **54''** may have a VSWR response that is a Chebyschev polynomial with a controlled ripple. This is accomplished by adjusting the length of the spacers **17a''**, **17b''**, **17c''**, **17d''** away from ¼ wavelength length at the resonance of the loop electrical conductor **13''**. Thus the loop electrical conductor **13''** and the spacers **17a''**, **17b''**, **17c''**, **17d''** have different resonant frequencies. As can be appreciated, the spacers **17a''**, **17b''**, **17c''**, **17d''** form transmission line stubs parallel to the loop electrical conductor **13''** feedpoints. In an example multiple tuned antenna, the lengths of the spacers **17a''**, **17b''**, **17c''**, **17d''** may be 0.31 wavelengths long when the circumference of the loop electrical conductor **13''** is 0.88 wavelengths, for example. In this instance the loop impedance is capacitively reactive when the spacers **17a'', 17b'', 17c'', 17d''** are inductively reactive, and the net effect is multiple resonances **51'', 52''**, a Chebyschev rippled VSWR response, and an increased VSWR bandwidth.

The feed network **16a''**, **16b''**, **16c''**, **16d''** may be in the form of four delay lines, for example, as described above. In other embodiments, the feed network **16a''**, **16b''**, **16c''**, **16d''** 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 of 0°, 90°, 180°, 270°, respectively.

Advantageously, the reflector **40''** increases gain and bandwidth of the antenna **12''**. The reflector **40''** has a cup shape. A cup shaped reflector **40''** reduces sidelobe and backlobe radiation by shielding radiation from the loop electrical conductor **13''** as it encloses the half space behind the radiating element. Additionally, the mouth of the reflector **40''** may be sized to carry parasitically induced radio frequency currents that constructively reradiate to increase antenna directivity and gain. Thus, a cup shaped reflector may be advantageous for many reasons over a planar metal plate reflector, for example.

Simulated performance of an example antenna similar to the antenna **12**'' described above is described in the following table:

Table 2: Example Embodiment, Circularly Polarized Cup Loop Antenna

Antenna type	Circular loop plus cup shaped reflector
Loop electrical conductor geometry	toroidal
Loop electrical conductor major diameter	0.32 meters
Loop electrical conductor minor diameter	0.012 meters
Loop radiator material	copper
Cup reflector shape	Cylindrical with closed bottom
Cup reflector position	The radiating loop and the mouth of the reflector cup are in the same plane
Cup reflector outer diameter	0.6 meters
Cup reflector depth	0.25 meters
Cup reflector material	aluminum
Cup reflector electrical outer circumference at the first resonance of the loop	$1.76\lambda_{air}$
Polarization	Dual circular, left and right hand senses from separate ports
Number of ports in loop conductor	Four, equally clocked around the loop circumference
Loop port type	Small gap in loop conductor
Loop port excitation	Equal amplitude, phase quadrature (0, 90, 180, and 270 degree phase)
Current distribution on loop conductor	Traveling wave
Loop first resonant frequency	281 MHz

Loop electrical circumference at resonance	$0.94\lambda_{air}$
Impedance at loop ports at first resonance	About 55 + j0 ohms
Loop RF current distribution	Traveling wave: two current maxima move around loop circumference at an angular velocity of 2πf
RF current amplitude on the loop	4.1 amps with 1 watt transmitter
RF current amplitude along mouth of the cup reflector	0.2 amps with 1 watt transmitter
Antenna gain	7.6 dBic
Antenna 12 half power beamwidth	111 degrees
Antenna beam shape	Cos^n elevation cut, highly symmetrical in azimuth
VSWR response shape	Quadratic / single tuning
2 to 1 VSWR bandwidth	34 MHz
3 dB gain bandwidth	122 MHz

Referring now additionally to the graph in FIG. 10, a simulated radiation pattern **51’’** for the antenna **12’’** is illustrated with 7.6 dBic gain. The radiation pattern **51’’** corresponds to the Y-Z and X-Y axes, is an elevation plane cut profiling the antenna beam, and is nearly symmetric. As will be appreciated by those skilled in the art, a symmetrical radiation pattern reduces interference with adjacent satellites, for example.

Referring now additionally to FIG. 11, according to another embodiment, the antenna **12’’’** includes three passive elements **19a’’’**, **19b’’’**, **19c’’’** each having a ring shape. Of course, the passive elements **19a’’’**, **19b’’’**, **19c’’’** may have another shape, and there may be a different number of passive elements. The first passive element **19a’’’** is illustratively spaced apart from the loop electrical conductor **13’’’** and has a smaller circumference than the loop electrical conductor. The circumference of each of the passive elements **19’’’** is successively smaller based upon the distance from the loop electrical conductor **13'''**. For example, the first passive element **19a'''** may have a circumference corresponding to 0.9λ, and may be spaced from the loop electrical conductor **13'''** by 0.2λ, the second passive element **19b'''** may have a circumference corresponding to 0.8λ, and may be spaced from the first passive element by 0.2λ, and the third loop electrical conductor **19c'''** may have a circumference corresponding to 0.7λ, and may be spaced from the second loop electrical conductor by 0.2λ. Each passive element **19'''** may maintain a constant spacing between adjacent loop electrical conductors, for example, 0.2λ. Of course, the passive elements **19'''** may be spaced by another distance or by non-constant distance, and the circumference of each passive elements may become successively smaller by at different intervals. If a large number of passive elements **19'''** are utilized the propagation velocity of an incoming electromagnetic wave will slow as the wave passes over the many passive elements **19'''**. In this case the spacing between the passive elements may be closer near the cup reflector end of the antenna **12'''** and less elsewhere. In other words, a nonconstant spacing may be preferential with the passive elements **19'''** "bunched up" near the cup reflector end of the antenna **12'''**.

Each of the passive elements **19'''** may be coupled to a respective spacing structure **45'''** that extends from the closed end **43'''** of the reflector **40'''**. The spacing structure **45'''** is not coupled to the feed network **16a'''**, **16b'''**, **16c'''**, **16d'''**. As will be appreciated by those skilled in the art, by adding additional passive elements **19'''**, the beam may become increasingly focused, and the antenna **12'''** may have increased gain.

The feed network **16a'''**, **16b'''**, **16c'''**, **16d'''** is in the form of four delay lines, and as described above, and further includes digital delay processing circuitry **46'''**. The digital delay processing circuitry **46'''** 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 **46'''** may be used without the four delay lines. The digital delay processing circuitry **46'''** may also be configured to perform additional functions, for example, that of the power dividers **22'''**, **24'''**, **26'''**.

A method aspect is directed to a method of making an antenna to be used in a wireless communications device **10''**. The method includes forming a loop electrical conductor **13''** having four spaced apart gaps therein defining four respective spaced apart coupling points **14a''**, **14b''**, **14c''**, **14d''**. The method also includes forming a feed assembly by forming a feed network **16a''**, **16b''**, **16c''**, **16d''** and coupling the feed network between at least one antenna feed **18a''**, **18b''** and a respective one of the four coupling points **14a''**, **14b''**, **14c''**, **14d''**. The method further includes positioning a reflector **40''** to surround the loop electrical conductor **13''**.

Additional details of a wireless communications device including the antenna according to the present embodiments may be found in related application attorney docket Nos. GCSD-2490 and GCSD-2500, assigned to the present assignee, and the entire contents of each of which are herein incorporated by reference. Many modifications and other 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

an antenna coupled to said wireless communications circuitry and comprising

a loop electrical conductor having four spaced apart gaps therein defining four respective spaced apart coupling points,

a feed assembly comprising

at least one antenna feed,

a feed network coupled between said at least one antenna feed and said four coupling points, and

a reflector surrounding said loop electrical conductor.

2. The wireless communications device of Claim 1, wherein said reflector comprises a cylindrically shaped body having an open end and an opposing closed end carrying said loop electrical conductor.

3. The wireless communications device of Claim 1, wherein said antenna further comprises at least one passive element carried by said reflector and spaced apart from said loop electrical conductor.

4. The wireless communications device of Claim 3, wherein said at least one passive element comprises a plurality thereof having ring shapes and with circumferences that decrease in size as a distance from said loop electrical conductor increases.

5. The wireless communications device of Claim 1, wherein the spaced apart coupling points are separated by one quarter of a length of the loop

electrical conductor; and wherein the length of said loop electrical conductor corresponds to an operating wavelength of said antenna.

6. A method of making an antenna to be used in a wireless communications device comprising:

forming a loop electrical conductor having four spaced apart gaps therein defining four respective spaced apart coupling point;

forming a feed assembly by forming a feed network between at least one antenna feed and a respective one of the four coupling points; and

positioning a reflector to surround the loop electrical conductor.

7. The method of Claim 6, wherein positioning the reflector comprises positioning a cylindrically shaped body having an open end and an opposing closed end carrying the loop electrical conductor.

8. The method of Claim 6, further comprising forming at least one passive element carried by the reflector and spaced apart from said loop electrical conductor.

9. The method of Claim 8, wherein forming the at least one passive element comprises a forming a plurality thereof having ring shapes and with circumferences that decrease in size as a distance from the loop electrical conductor increases.

10. The method of Claim 6, wherein forming the feed assembly by forming a feed network comprises forming the feed assembly by forming digital delay processing circuitry.

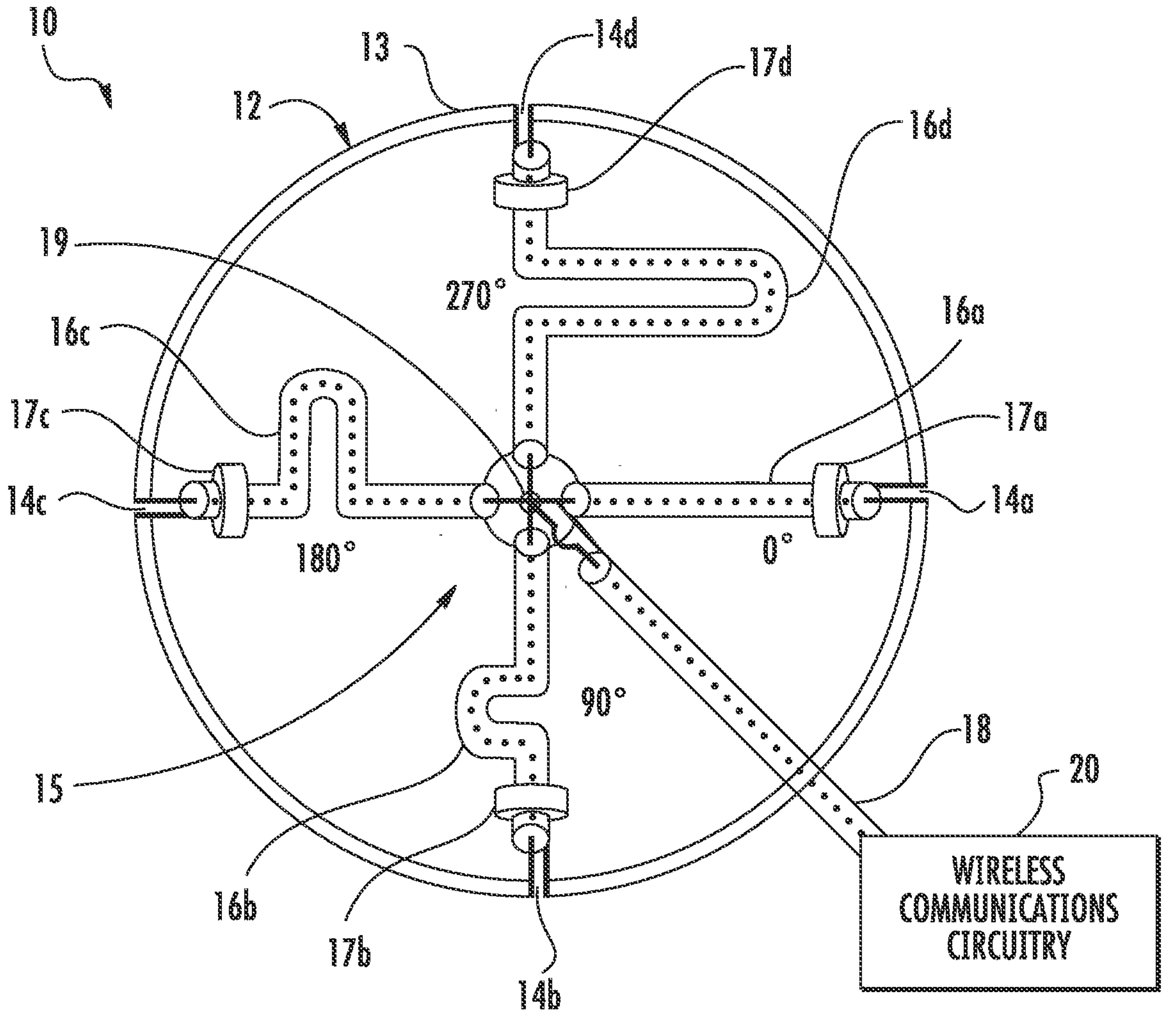
10
13
14d
17d
12
16d
19
270°
16a
16c
17a
17c
14c
14a
180°
0°
90°
18
15
20
WIRELESS COMMUNICATIONS CIRCUITRY
16b
17b
14b

FIG. 1

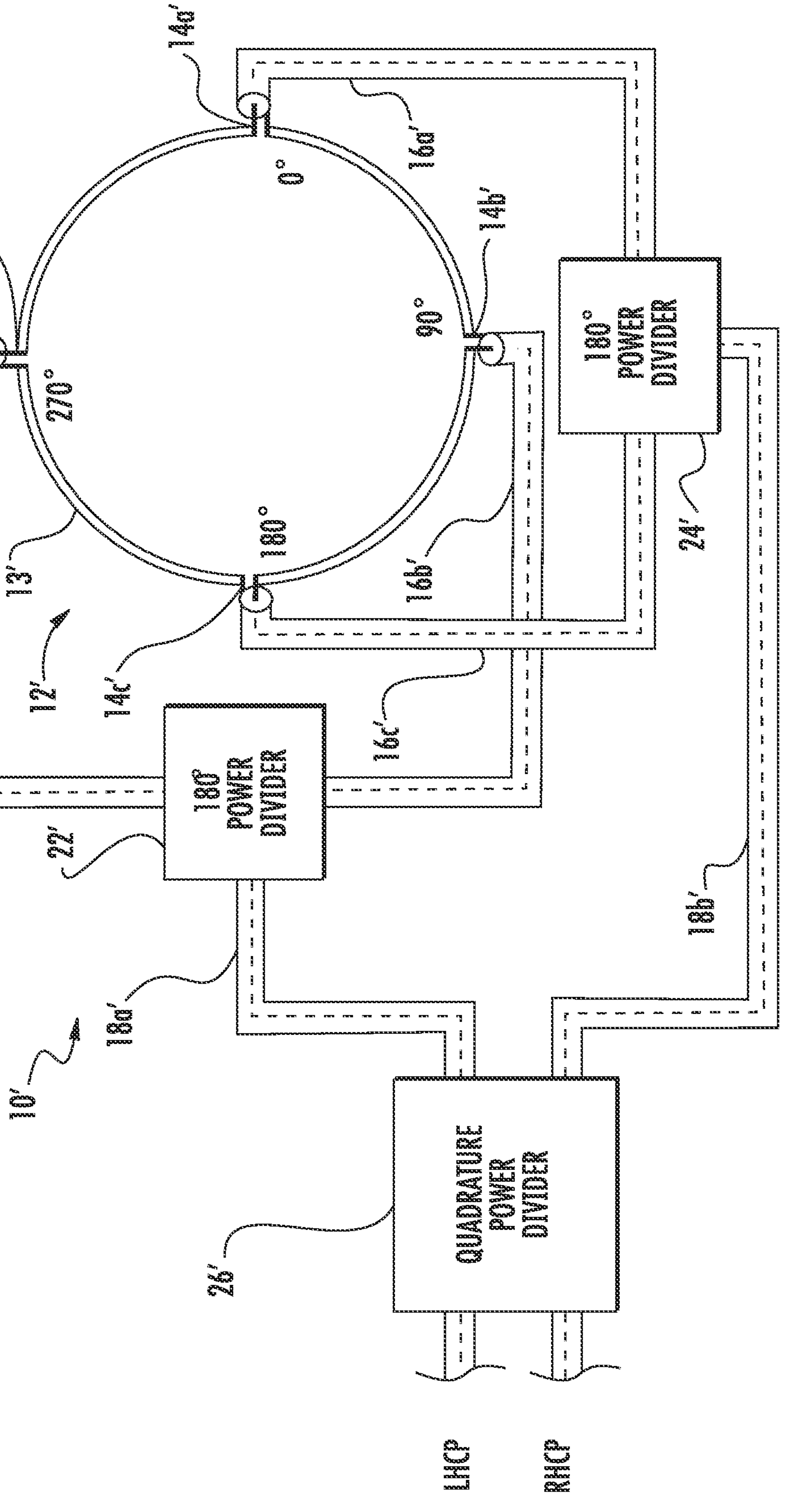
14a'
16a'
0°
14d'
14b'
16d'
90°
180° POWER DIVIDER
270°
180°
24'
16b'
13'
12'
14c'
16c'
180° POWER DIVIDER
22'
18b'
18a'
10'
QUADRATURE POWER DIVIDER
26'
LHCP
RHCP

FIG. 2

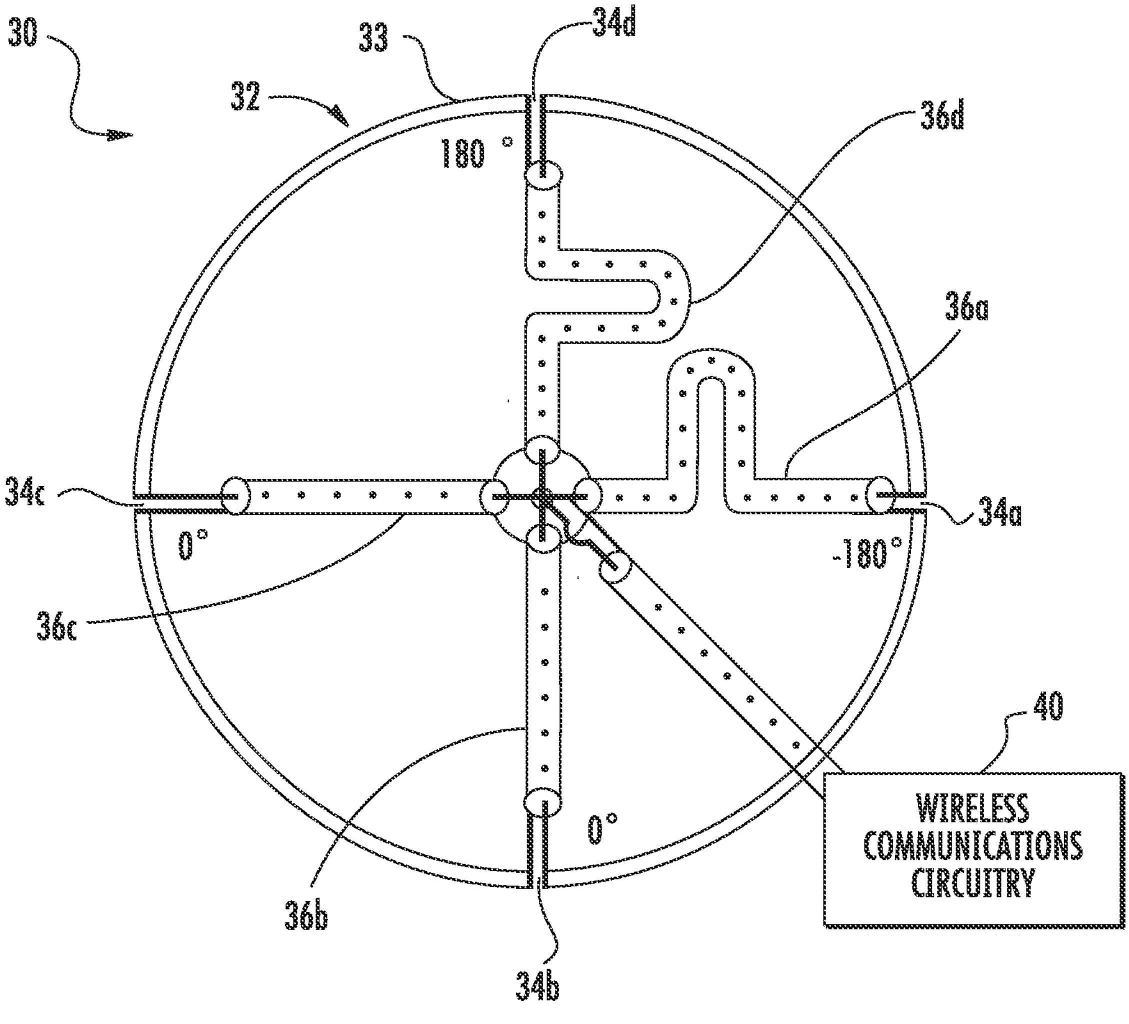
30
33
34d
32
180 °
36d
36a
34c
34a
0°
-180°
36c
40
WIRELESS COMMUNICATIONS CIRCUITRY
0°
36b
34b

FIG. 3

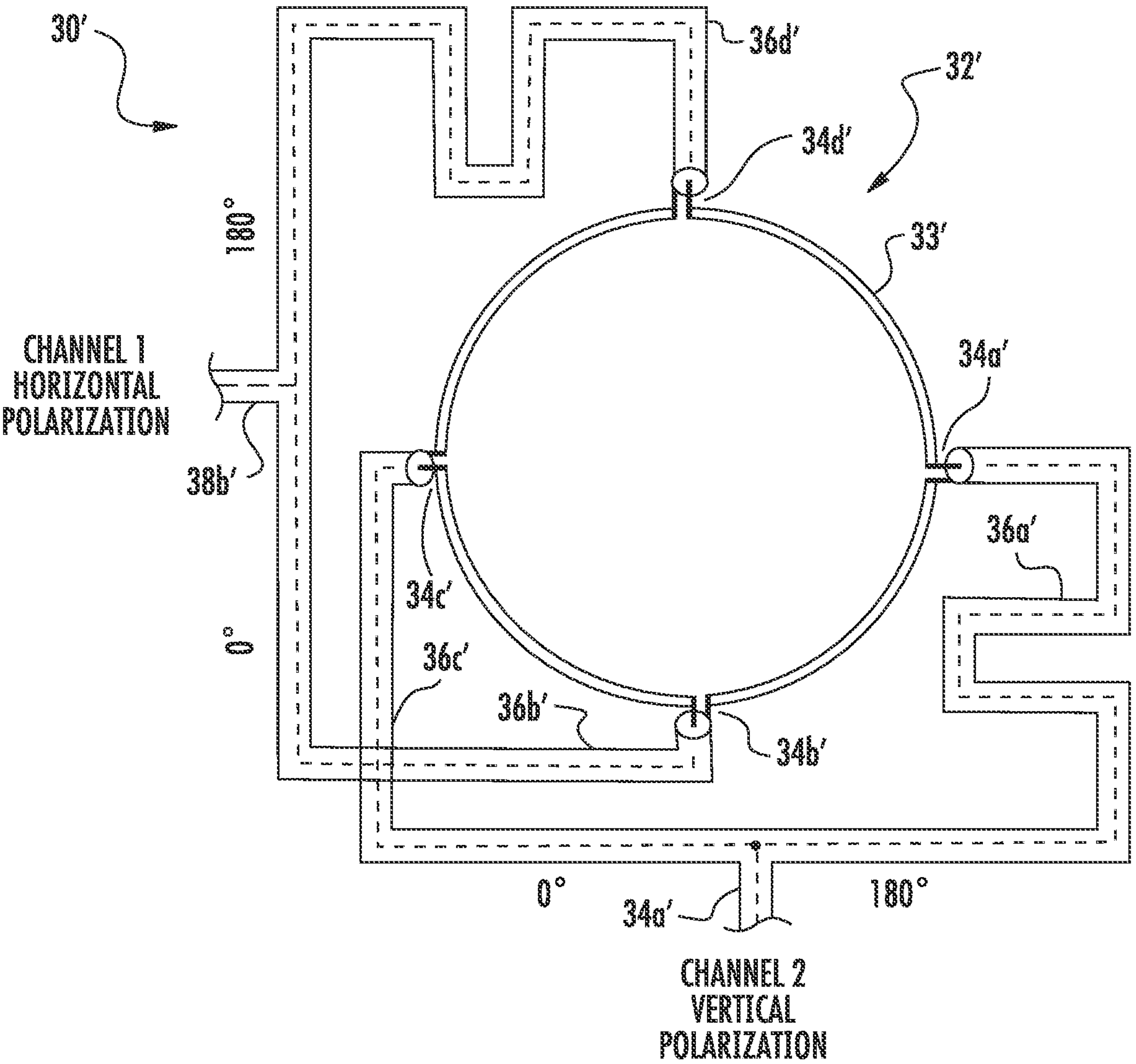
30'
36d'
32'
34d'
180°
33'
CHANNEL 1
HORIZONTAL
POLARIZATION
34a'
38b'
36a'
34c'
0°
36c'
36b'
34b'
0°
34a'
180°
CHANNEL 2
VERTICAL
POLARIZATION

FIG. 4

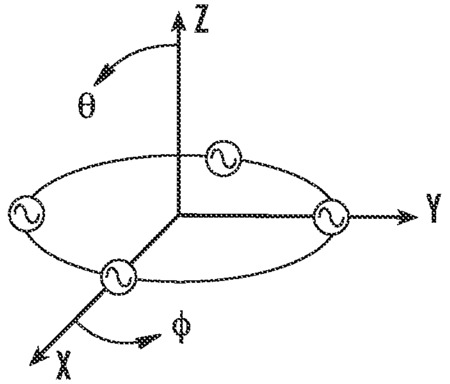

FIG. 5A

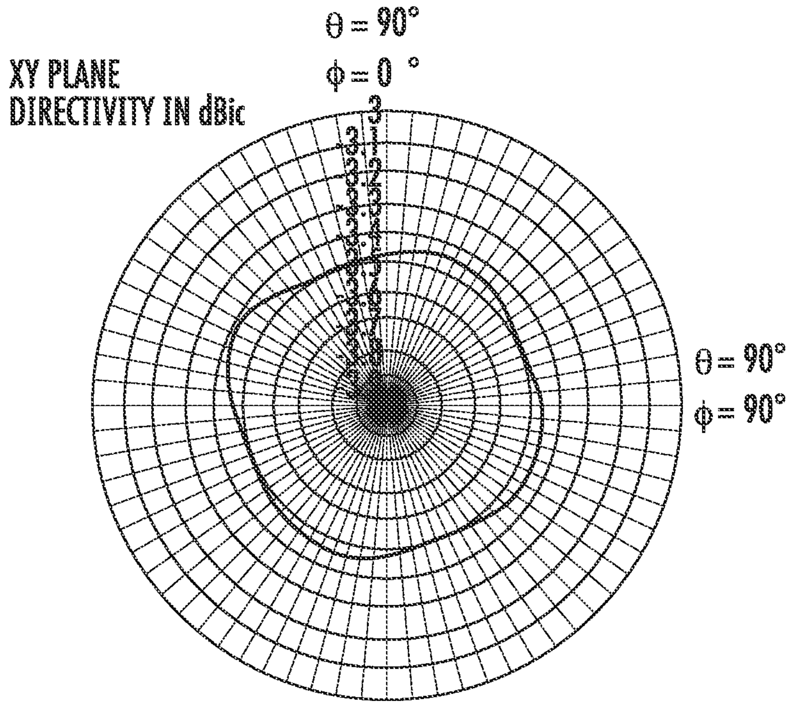

FIG. 5B

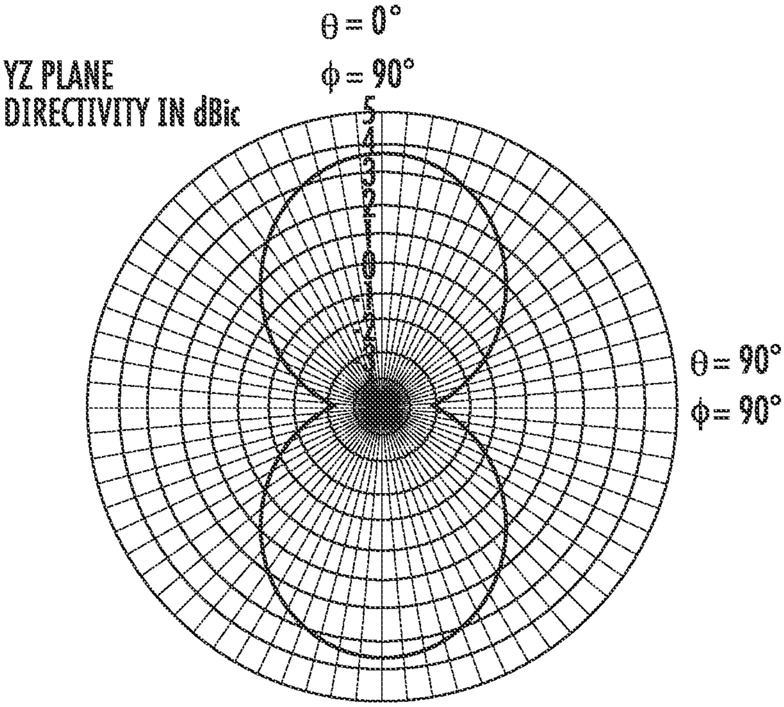
θ = 0°
φ = 90°
YZ PLANE
DIRECTIVITY IN dBic
5
4
3
2
1
0
θ = 90°
φ = 90°

FIG. 5C

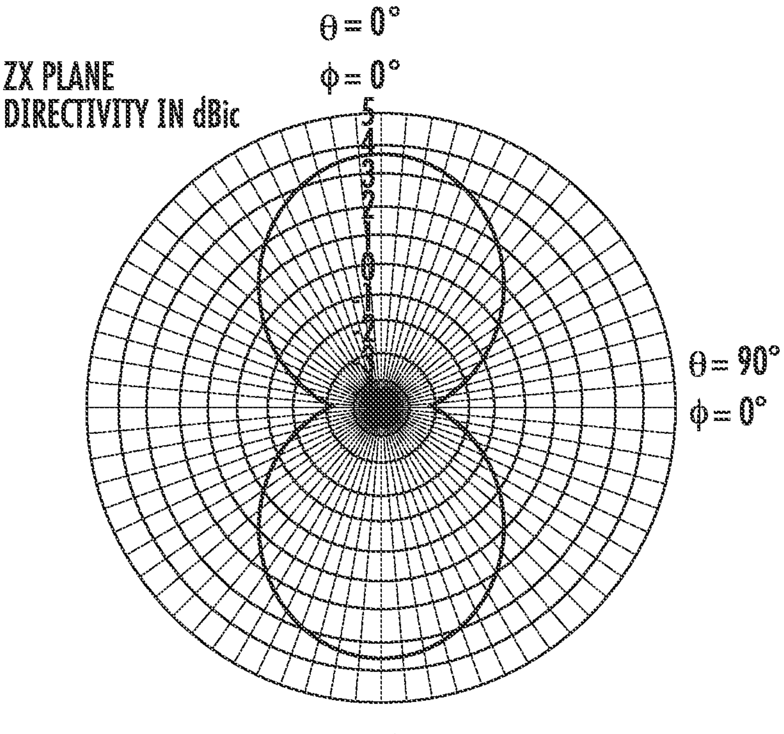
θ = 0°
φ = 0°
ZX PLANE
DIRECTIVITY IN dBic
5
4
3
2
1
0
θ = 90°
φ = 0°

FIG. 5D

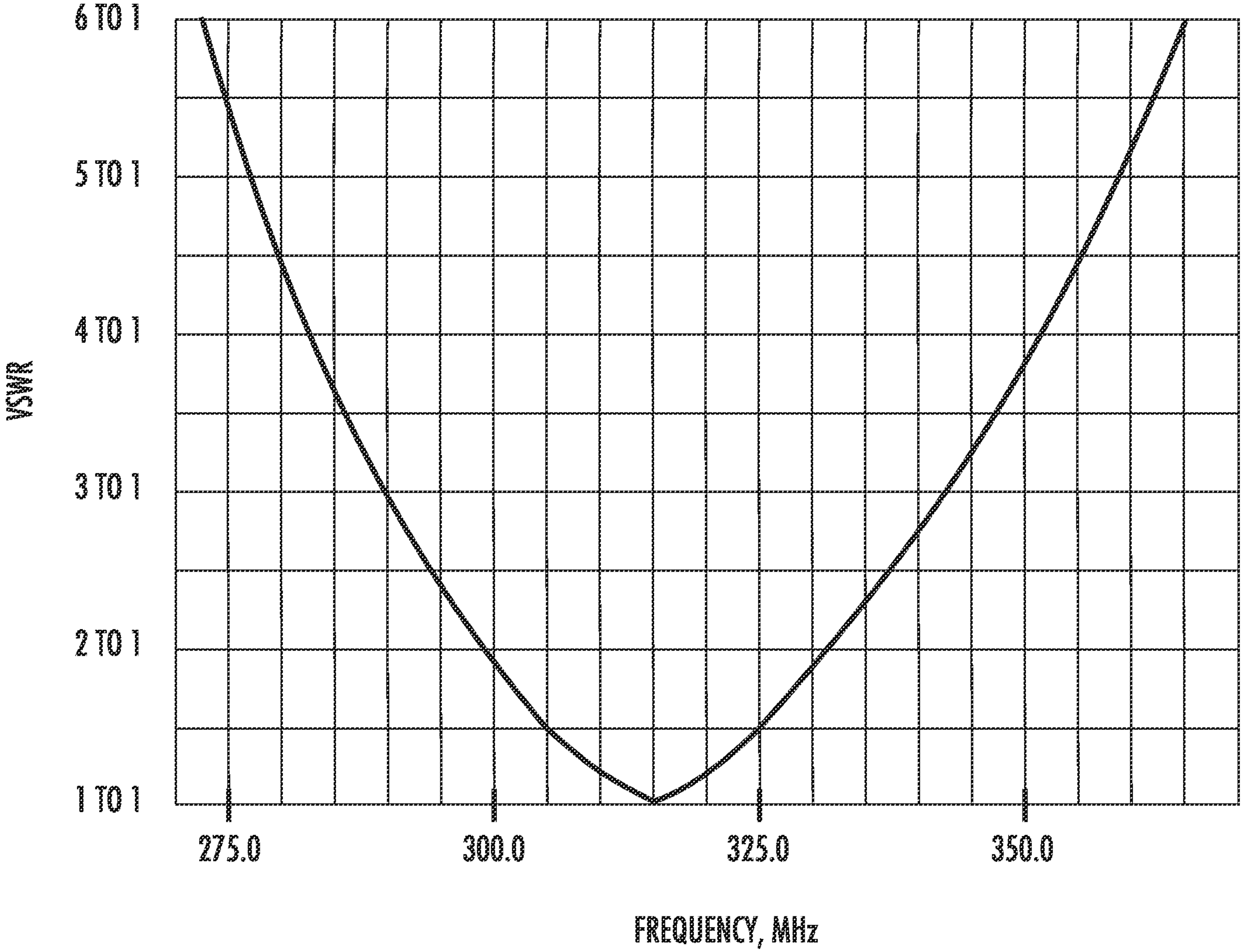
6 TO 1
5 TO 1
4 TO 1
3 TO 1
2 TO 1
1 TO 1
VSWR
275.0
300.0
325.0
350.0
FREQUENCY, MHz

FIG. 6

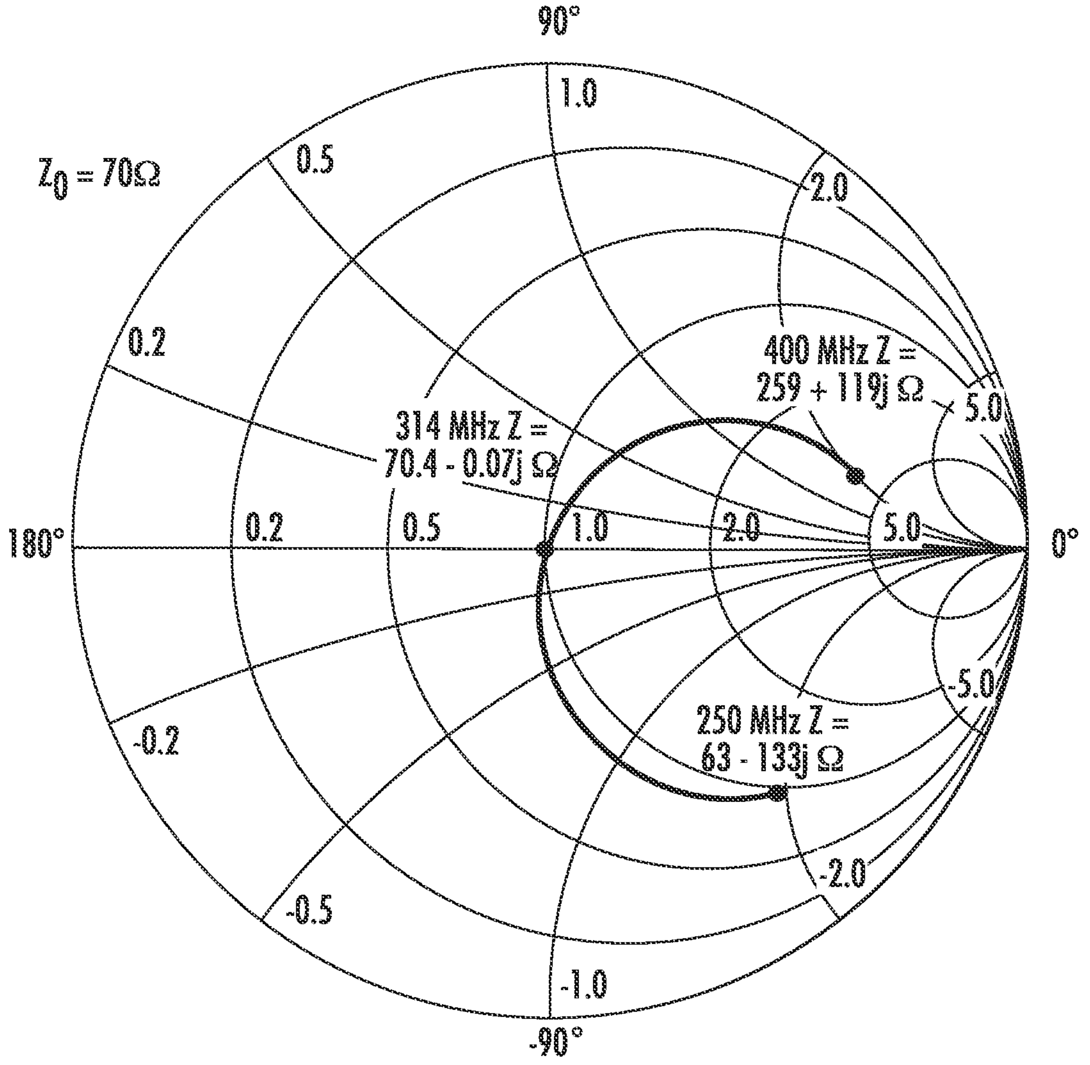
90°
1.0
0.5
2.0
Z_0 = 70Ω
0.2
400 MHz Z ≈
259 + 119j Ω
5.0
314 MHz Z ≈
70.4 - 0.07j Ω
180°
0.2
0.5
1.0
2.0
5.0
0°
-5.0
250 MHz Z ≈
63 - 133j Ω
-0.2
-2.0
-0.5
-1.0
-90°

FIG. 7

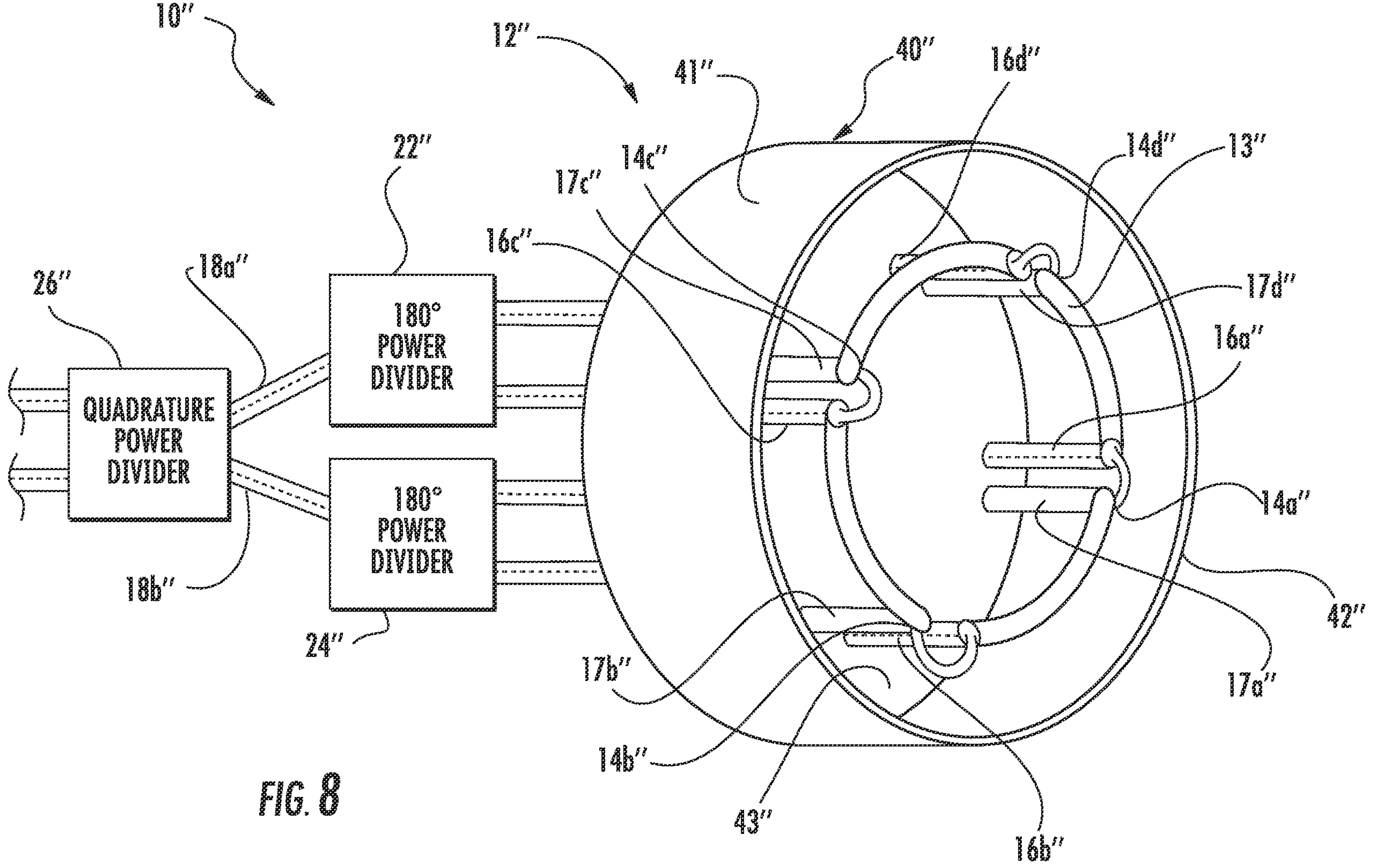
10''
12''
40''
41''
16d''
14d''
13''
22''
14c''
17c''
16c''
26''
18a''
180°
POWER
DIVIDER
QUADRATURE
POWER
DIVIDER
17d''
16a''
180°
POWER
DIVIDER
14a''
18b''
24''
42''
17b''
17a''
14b''
43''
16b''

FIG. 8

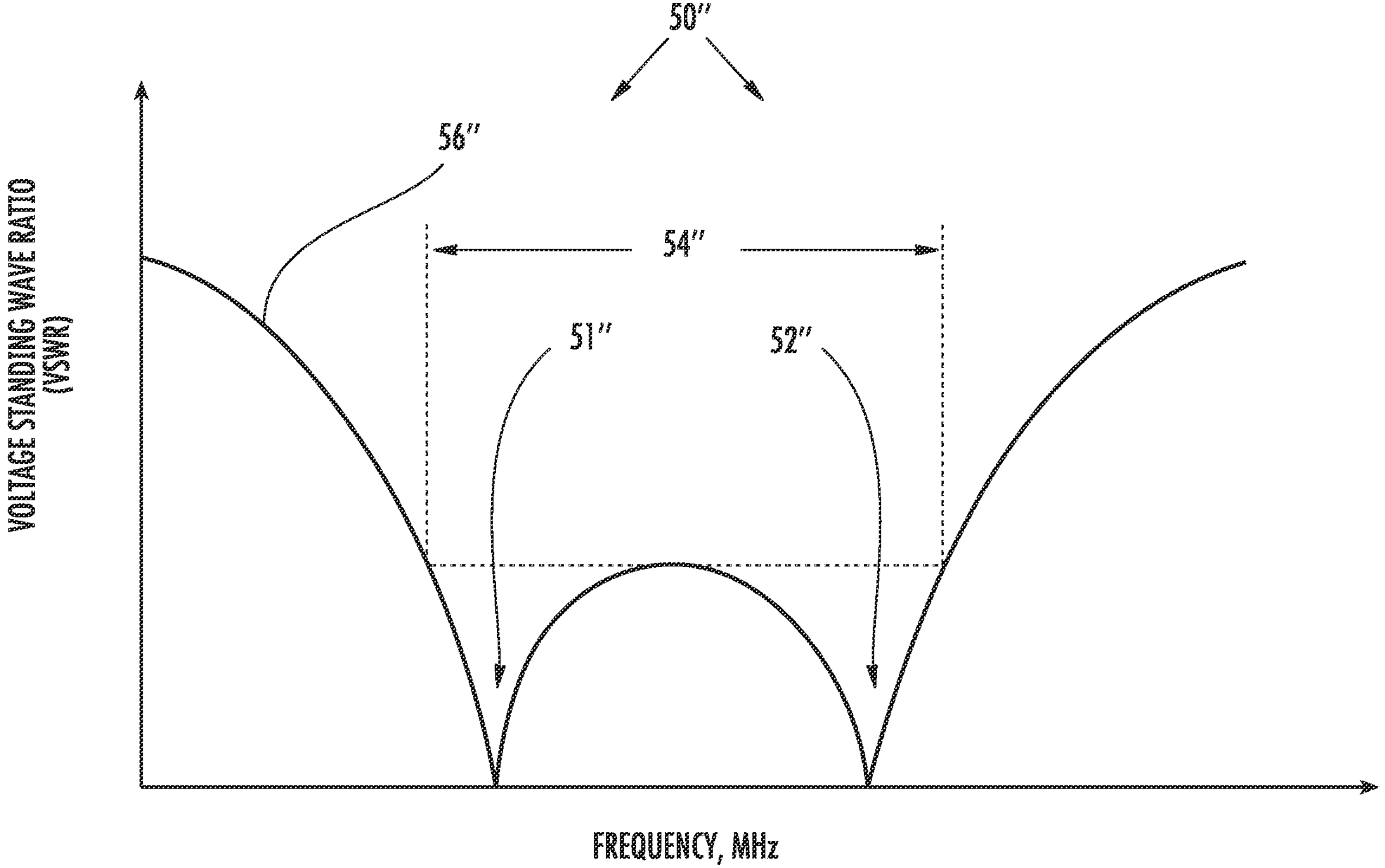
50″
56″
54″
51″
52″
VOLTAGE STANDING WAVE RATIO (VSWR)
FREQUENCY, MHz

FIG. 9

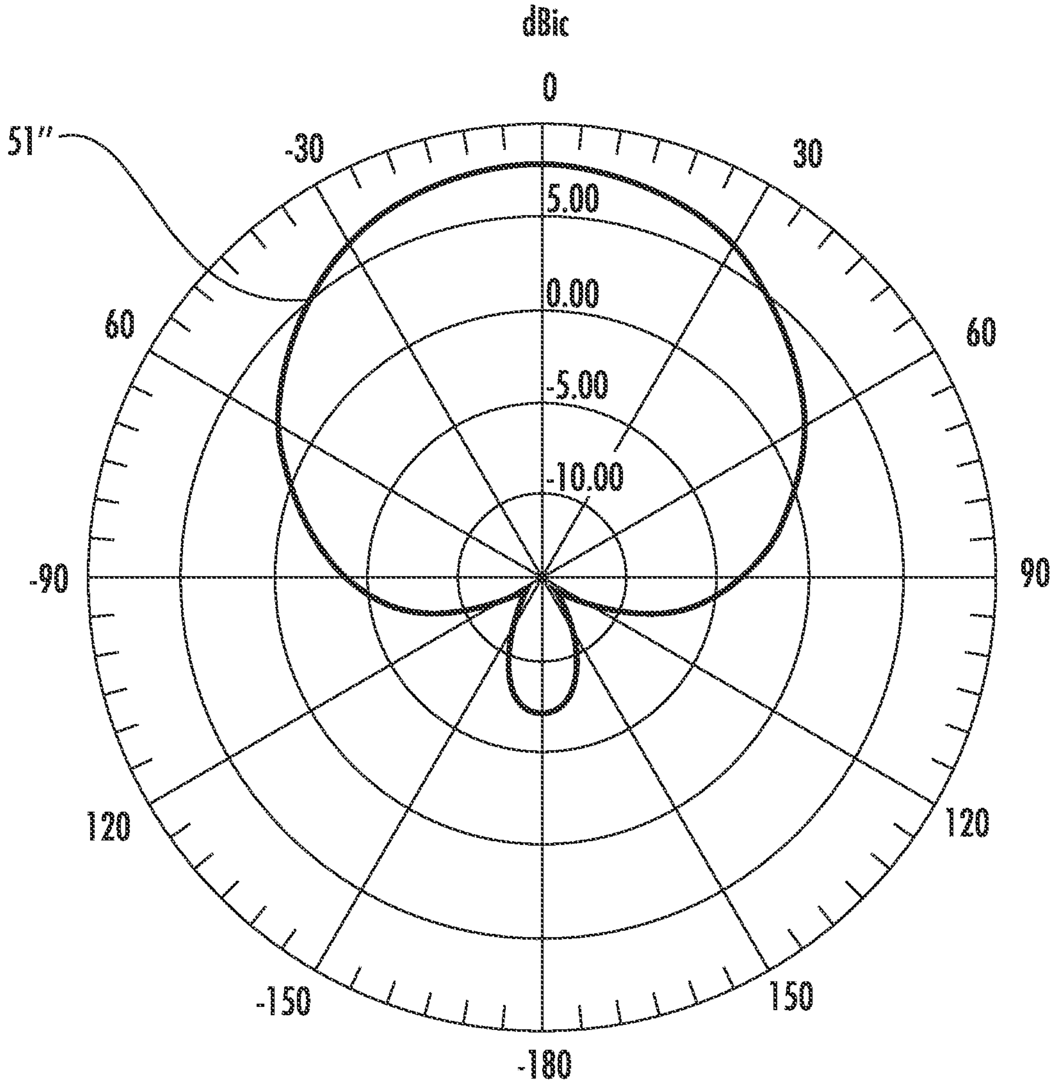

FIG. 10

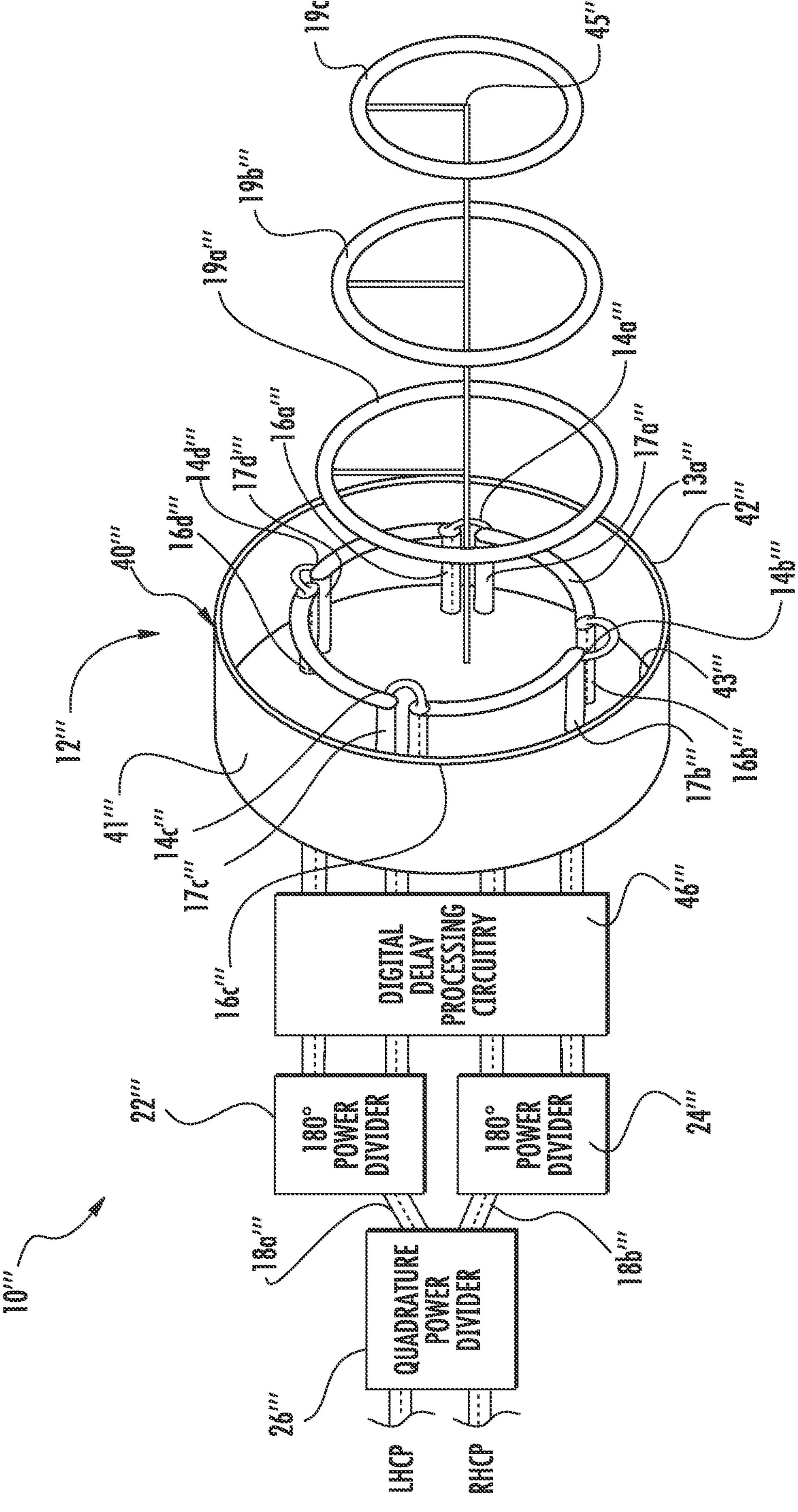
10'''
12'''
40'''
41'''
14c'''
17c'''
16c'''
16d'''
14d'''
17d'''
16a'''
14a'''
17a'''
13a'''
42'''
14b'''
43'''
16b'''
17b'''
19a'''
19b'''
19c'''
45'''
DIGITAL DELAY PROCESSING CIRCUITRY
46'''
22'''
180° POWER DIVIDER
24'''
180° POWER DIVIDER
18a'''
18b'''
QUADRATURE POWER DIVIDER
26'''
LHCP
RHCP

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2013/023525

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01Q7/00 H01Q19/10 H01Q21/24

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.
Y	US 2008/136720 A1 (PARSCHE FRANCIS EUGENE [US] ET AL) 12 June 2008 (2008-06-12) paragraph [0031] - paragraph [0050]; figures 1-5 -----	1-10
Y	EP 2 226 895 A2 (DELPHI DELCO ELECT EUROPE GMBH [DE]) 8 September 2010 (2010-09-08) paragraph [0054]; figure 19 -----	1-10
Y	US 2003/174098 A1 (NORO JUNICHI [JP] ET AL) 18 September 2003 (2003-09-18) paragraph [0057] - paragraph [0059]; figures 5-7 -----	1-10
Y	US 3 491 361 A (CAMPBELL RALPH W) 20 January 1970 (1970-01-20) column 3, line 56 - line 75; figure 1 ----- -/--	1-10

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

* Special categories of cited documents :

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"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 23 April 2013	Date of mailing of the international search report 29/04/2013
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Kaleve, Abraham

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/023525

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 2 490 815 A (KANDOIAN ARMIG G) 13 December 1949 (1949-12-13) column 2; figures 1,3 -----	1-10
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2013/023525

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			EP	2226895	A2	08-09-2010
			US	2010253587	A1	07-10-2010
US 2003174098	A1	18-09-2003	CN	1435950	A	13-08-2003
			US	2003174098	A1	18-09-2003
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			DE	69321561	D1	19-11-1998
			DE	69321561	T2	01-04-1999
			EP	0600799	A1	08-06-1994
			ES	2125317	T3	01-03-1999
			FR	2699008	A1	10-06-1994
			US	5659322	A	19-08-1997
US 2490815	A	13-12-1949	BE	463047	A	23-04-2013
			BE	463048	A	23-04-2013
			CH	269001	A	15-06-1950
			ES	172153	A1	16-02-1946
			FR	920588	A	11-04-1947
			NL	69932	C	23-04-2013
			US	2490815	A	13-12-1949
US 3740754	A	19-06-1973	NONE			