A Novel GPS Survey Antenna

Waldemar Kunysz, *NovAtel Inc.*

BIOGRAPHY

Waldemar Kunysz obtained a BSEE from the Technical University of Nova Scotia in 1989. From 1991 to 1995 he worked on phased array antennas for Microwave Landing Systems with Micronav Inc. From 1995 to the present he has been with NovAtel Inc. He has published several technical papers and proceedings articles for various conferences. His current research interests include antenna theory and design, multipath mitigation techniques, genetic algorithms and electromagnetic compatibility.

ABSTRACT

A novel GPS antenna for surveying applications is proposed. It is a fixed beam phased array of aperture-coupled slots optimized to receive a right hand polarized signal. The proposed antenna is made out of a single PCB board. Another PCB board is placed underneath the antenna to act as a reflector in order to reinforce the antenna directivity and reduce the back-lobe radiation. The radiation pattern roll-off of this antenna is sharper than the conventional GPS patch antennas mounted in the "choke ring" configuration. The sharp pattern roll-off allows reducing the antenna's susceptibility to multipath generated replicas of the GPS signal. The antenna is much smaller and lighter than a corresponding typical "choke ring" antenna. There is no phase center offset between the L1 and L2 GPS frequencies and the antenna does not require any alignment with respect to a given direction (such as North) due to its natural symmetry. Due to its planar structure it can be easily buried in the vehicle or aircraft skin.

INTRODUCTION

GPS antenna requirements differ in various applications. For precise surveying applications, ideally the antenna should receive only signals above the horizon and reject all signals below the horizon plane of the antenna, have a known and stable phase center that is co-located with the geometrical center of the antenna, and have perfect circular polarization characteristics to maximize the reception of the incoming right hand polarized (RHP) signal. A typical measure of merit of antenna polarization characteristics is Axial Ratio (AR). For dual frequency operation (L1 and L2), the antenna should also have a common phase center at both frequencies and ideally the same radiation pattern and axial ratio characteristics. There is, of course, no antenna that could meet all these requirements. The closest antenna that meets most of these requirements, to some degree, is a patch antenna mounted on a choke ring ground plane. Such an antenna is, however, large, bulky, heavy and relatively expensive, prohibiting its use in various applications. The new antenna presented in this paper is light and small and does not require a choke ring ground plane to achieve performance similar or better to a patch antenna in the choke ring ground plane configuration.

CHOKE RING GROUND PLANE ANTENNA

In order to see the benefit of the new antenna, we need to understand what type of performance is achieved with a patch antenna mounted in the choke ring ground plane configuration. We will use the following figures of merit: Axial Ratio, antenna amplitude directivity pattern roll-off (elevation plane), antenna amplitude directivity pattern variation in azimuth plane, phase center location and phase center variation.

Choke ring ground planes are a circular shaped ground plane with quarter wavelength slots that are shorted at the bottom and open at the top. This translates to a very high impedance ground plane that does not support image currents generated within the ground plane that normally would interfere with the currents generated within the patch antenna itself. This feature translates to very low side-lobes underneath the antenna horizon and very smooth amplitude and phase patterns generated by the antenna. In addition, very good Axial Ratio values (less than 3 dB) above 10 deg. elevation angle are achieved. The large size of the ground plane, on the other hand, translates to sharper amplitude roll-off (from zenith to the horizon) and increased main beam directivity of the antenna. Typical roll-off is in order of 10 to 12 dBi from zenith (90° elevation angle) to horizon (0° elevation angle) as compared to 3-5 dB roll-off of the patch antenna itself. Typical increase in the main beam directivity is in order of 1-2 dBi as compared to a stand-alone patch antenna without the choke ring ground plane. This performance enhancement is paid for with the size and weight of the additional ground plane. Typical diameter size of the choke ring is in the order of 14" to 16" and a weight of 10-20 lbs.

In dual frequency operation, the phase center offset is inherited from the patch antenna itself. Since patch antennas use a stack configuration in order to resonate at two frequencies, they have a natural vertical offset between L1 and L2 phase centers that cannot be compensated for with a choke ring ground plane. Good surveying antennas currently available on the market have a typical L1-L2 offset in the order of 5-20mm. For high-end applications such as tectonic movement monitoring this offset must be corrected for, especially for very long GPS baseline measurements.

Microstrip patch antennas with stable phase centers must be fed in at least two points, preferable in four points (for all four edges of rectangular/square patch). Since the antenna must be circularly polarized, a 90° phase gradient must be established between the feeding points. The feed network to establish a 90° phase gradient for a two point feed system is relatively simple (90° hybrid will do), however as the number of feeds is increased the feed network becomes more complex and lossy.

NEW ANTENNA CONCEPT

The new, patent pending, antenna is not a patch antenna but an array of multiple spiral slots that are electromagnetically coupled to a feeding network. Let's refer to it as an aperture coupled slot array antenna and denote it as a pinwheel type antenna, due to its internal layout nature. See Figure 1 for a board layout of a 4-arm spiral pinwheel antenna.

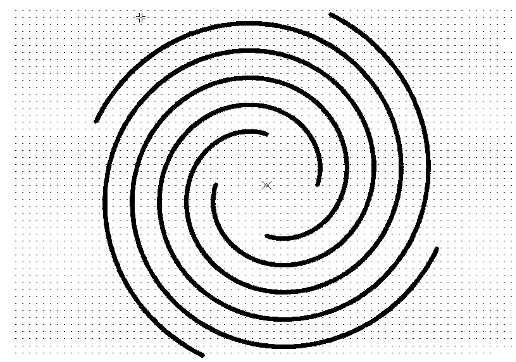


Figure 1. PCB layout for four-arm spiral L1 antenna

The actual antenna developed for production has 12 arms. The spatial difference between each two consecutive spiral arms is 30°, as well the electrical phase length of the feeding network is set to 30°. This arrangement allows having a more stable phase center (12 feeding points versus 4) and achieving excellent circular polarization. The feeding network is a leaky wave microstrip circuit in order to avoid complexity, keep it simple and maintain uniform amplitude excitation for all slots.

The pinwheel antenna is designed to operate at two L1 and L2 bands of GPS and Glonass navigation systems. Six spiral arms resonate at L1 band and the other six arms resonate at L2 band. L1 and L2 spiral arms are interleaved to maintain a natural symmetry of the antenna in all three axes: x, y and z. The pinwheel antenna is made out of a flat printed circuit board (PCB), with the upper layer being the ground plane layer.

Having the ground plane as the top layer provides an additional shielding against electromagnetic pulses generated by lightning or human related activities. In addition, the electric field is forced to zero (boundary condition) for the signals tangential to the ground plane (antenna horizon). This feature translates to a sharp amplitude pattern roll-off near horizon, available only with choke ring ground plane or with extremely large ground planes (diameter in excess of 18-20"). The typical amplitude roll-off is 12 dB at L1 band and 15 dB at L2 band. This performance is achieved with a diameter of only 6.25". In addition, the antenna is very light (500 grams) which make this antenna easily adaptable to any surveying applications.

There is no phase center offset between L1 and L2 bands for all three axes (x, y and z), due to the following features of this antenna:

1. Natural symmetry of all slots with respect to geometrical center of antenna.
2. L1 and L2 slots are interleaved to maintain symmetry between both bands.
3. All L1 and L2 slots are contained in the same z-axis plane, since no vertical offset in physical layout exists between the slots.

To maintain a good front/back ratio a thin metal reflector is placed underneath the antenna board. This prevents the multipath generated replicas of GPS or Glonass signals to be amplified by the antenna. In the current configuration the ground plane of the Low Noise Amplifier (LNA) is used as an antenna's reflector.

ANECHOIC CHAMBER MEASUREMENTS

The antenna performance was validated by performing detailed anechoic chamber measurements and various GPS live signal tests. The main purpose of the anechoic chamber measurements was to determine the phase center location, its stability and amplitude radiation patterns. The horizontal phase center variation from the geometrical phase center of the antenna is shown on the next two graphs.

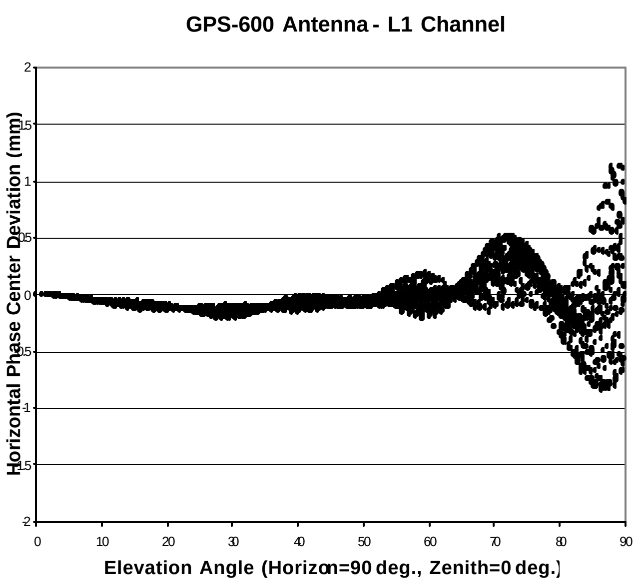
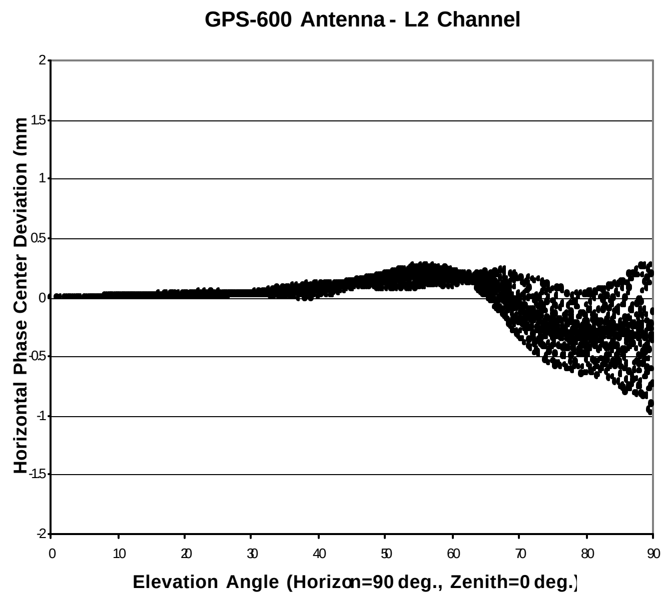


Figure 2. L1 Channel phase center variation in horizontal plane for 12-arm L1/L2 antenna (GPS-600)

One shall keep in mind that antenna boresight angle 0° corresponds to a GPS elevation angle of 90° and vice-



versa antenna angle of 90° corresponds to a GPS elevation angle of 0° (Horizon plane).

Figure 3. L2 Channel phase center variation in horizontal plane for 12-arm L1/L2 antenna (GPS-600)

As we can see the horizontal variation is very small (less than 0.2mm for GPS elevation angles of 20° or more). The L1-L2 offset, in horizontal plane, is less than 0.5 mm for the same angle range, which is below the noise of GPS measurements.

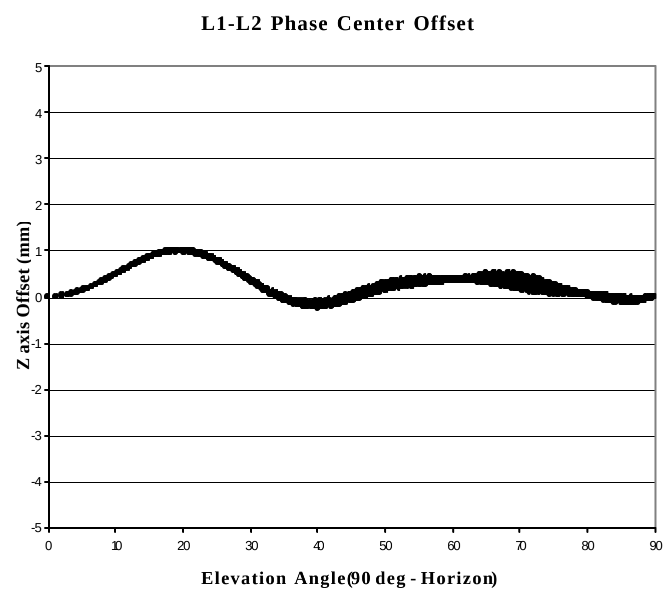


Figure 4. L1-L2 channel phase center offset variation in vertical plane for 12-arm L1/L2 antenna

The average vertical (z-axis) offset between the L1 and L2 channels is less than 1mm (see Figure 4). This feature is very important for antenna network installations using very long baselines (over 1000 km). All base station antennae used for very long GPS baselines are basically choke ring type antenna that have a physical offset between the L1 and L2 channel in the order of 5-20 mm. Typical patch antennas have this type of vertical offset between L1 and L2 channels due to the physical vertical offset between two patches

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The antenna phase center does move in vertical plane (z-axis) for each channel, which is inherently unavoidable with any antenna beam that is highly directive. A perfect phase center antenna of an imaginary ideal antenna would have to have the same amplitude and phase pattern in every direction, whether it is zenith or horizon of the antenna. This would cause the antenna to be severely susceptible to multipath. So in order to deal with the multipath a compromise must be made – shape the amplitude radiation pattern to reduce the reception of multipath signal generated at low elevation angles (near horizon) and allow the phase center to vary with elevation angle (movement along z-axis). This goal was achieved with the antenna described in this paper. The maximum vertical variation of the phase center is 14 mm. This phase center offset is cancelled out when using same type antennas or it can be corrected for in a post mission processing. The phase center movement with elevation angle is usually tabulated and corrected by software in the GPS receiver.

A typical amplitude radiation pattern characteristic is shown on the next two graphs (Figures 5 and 6). The amplitude roll-off from antenna boresight to horizon is about 15dB, which compares very well with the patch antenna mounted on the choke ring ground plane. In addition, the peak antenna directivity is 10 dBi for L1 channel and 8.5 dBi for L2 channel. A typical high performance patch antenna has peak directivity of 3-6 dBi and up to 5-8 dBi when mounted in choke ring ground plane.

The additional antenna directivity allows acquiring low elevation angle satellites as well as provides higher C/No values for satellites located at high elevation angles. This directly translates to less noisy phase carrier measurements and better RTK solution.

The measured Axial Ratio of the GPS-600 antenna was below 3 dB for satellite elevation angles from zenith (90°) down to 30°. The Axial Ratio degrades between elevation angle of 30° and horizon (0°) from 3 dB to 9 dB. The poor Axial Ratio near horizon is compensated for by sharp amplitude pattern roll-off towards horizon, thus ensuring that multipath generated signals are well attenuated by the antenna.

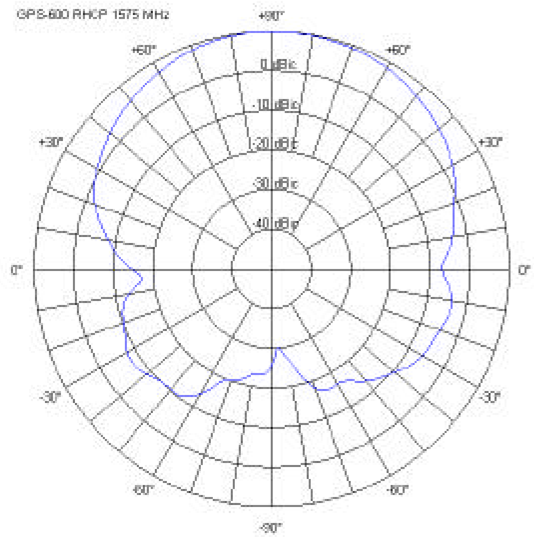

Figure 5. L1 Channel amplitude radiation pattern for 12-arm L1/L2 antenna

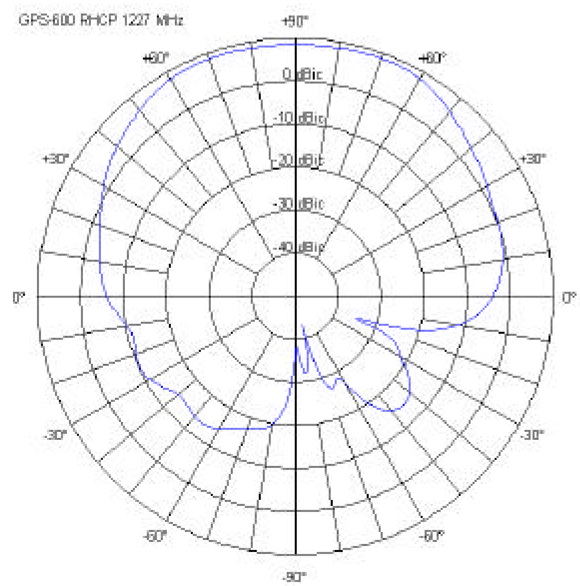

Figure 6. L2 Channel amplitude radiation pattern for 12-arm L1/L2 antenna

LIVE GPS SIGNAL MEASUREMENTS

The GPS antenna performance was validated by performing survey type measurements. The following figures of merits were used to determine the antenna performance: carrier to noise (C/No) variation with azimuth angle and elevation angle of tracked satellite, multipath susceptibility using NovAtel proprietary multipath meter indicator algorithms and short baseline (100 meter maximum) phase residuals.

C/No variation for both channels is shown on the next two graphs (Figures 7 and 8).

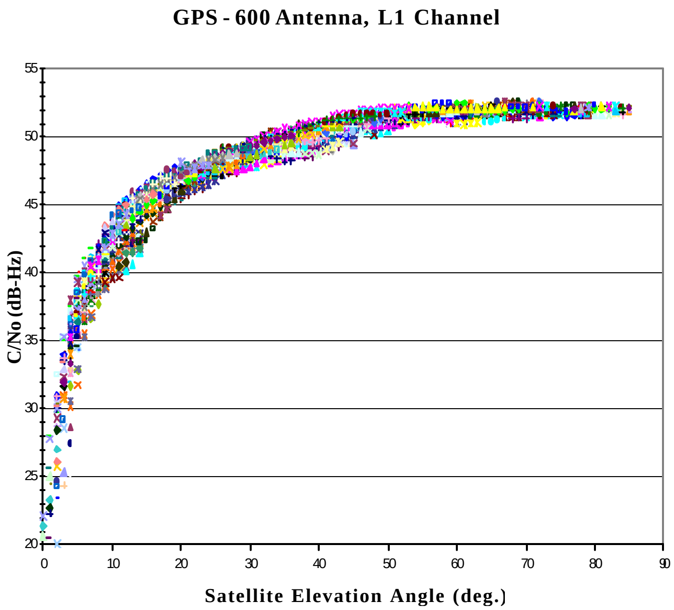

Figure 7. L1 Channel C/No for 12-arm L1/L2 antenna

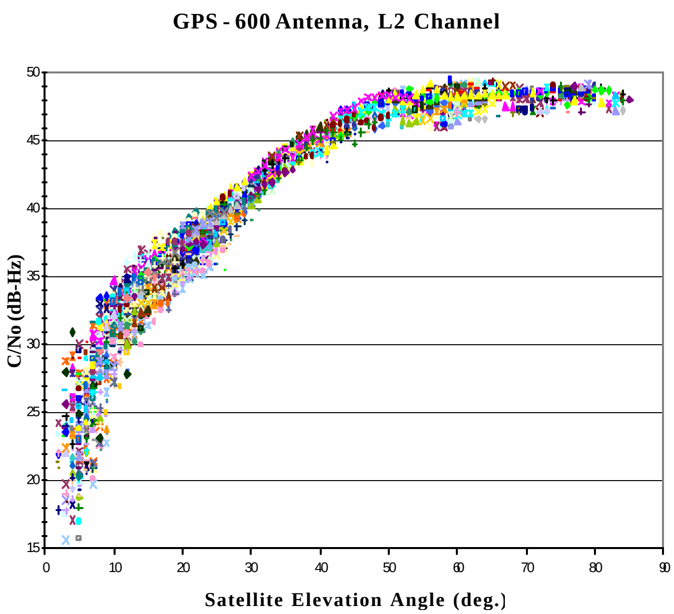

Figure 8. L2 Channel C/No for 12-arm L1/L2 antenna

The graphs show data collected over a 16 hour period for all satellites tracked in that period. The data was collected using NovAtel's L1/L2 MiLLennium™ GPS receiver. The variations of C/No for a given elevation angle are due mainly from two factors: antenna amplitude variation in azimuth plane, and transmitted signal variation between different GPS satellites. A sharp roll-off of C/No is observed at low elevation angles, which confirms the measurements made in an anechoic chamber. High C/No for high elevation angles is also confirmed, due to high directivity of the antenna and low level of thermal noise (1.5 dB typical) injected by the internal Low Noise Amplifier (LNA) of the antenna.

Multipath meter indicator indicates a level of multipath and noise generated by the site surrounding the antenna. The level of multipath, detected by the multipath meter, is shown in mm and is mainly dependent on the following:

- terrain profile and sky obstructions surrounding the antenna
- antenna's proper circular polarization (RHP)
- antenna's susceptibility to multipath (Axial Ratio, Pattern roll-off, Up-Down Ratio)
- receiver's multipath mitigation techniques (i.e. Narrow Correlator™, MEDLL™, etc.)

The next four graphs (Figures 9-12) show a multipath level observed on NovAtel's building roof using a choke ring antenna and the new antenna presented in this paper. The graphs show a sky view type projection with the zenith (90° elevation angle) being the center of the projection and the horizon (0° elevation angle) being the outside rim of the projection. The inner grid circles represent elevation angle of satellite in 5° increments. The North direction is pointing towards the top of the page.

One can observe an increased level of multipath coming from an azimuth sector from 045° to 090°, especially at elevation angle of 25°. This location corresponds to a metal fence located on a nearby hill that towers over the NovAtel building roof. The new antenna compares very well to choke ring antenna performance at both L1 and L2 frequency channel.

Note the fact, that the new antenna attenuates the signal near horizon (less than 5° elevation angle) to the point that no multipath statistics are available for that region.

The next GPS live signal figure of merit used was Baseline Residuals (see Figures 13 and 14). Two prototype antennas were mounted on tripods, near a metallic fence, in a location known for high multipath. The baseline was fixed at 125 meters. The same measurements were repeated the next day with two high performance patch antennas using the same configuration (satellite constellation, antenna positions, etc.). Baseline Residuals for each case were computed using SoftSurv™ processing software. From Figure 14, one can observe a scalloping effect for some satellites indicating susceptibility of the patch antenna to multipath generated by the metallic fence. In addition, a DC bias of baseline residuals of certain satellites (i.e. PRN#13) indicates a noticeable phase center variation. These deficiencies are not present with the pinwheel antennas (see Figure 13).

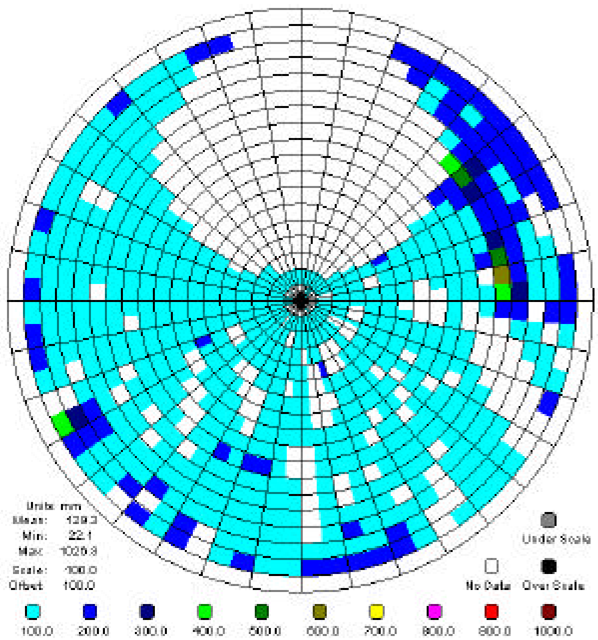

Figure 9. *L1 multipath in mm for 12-arm L1/L2 antenna*

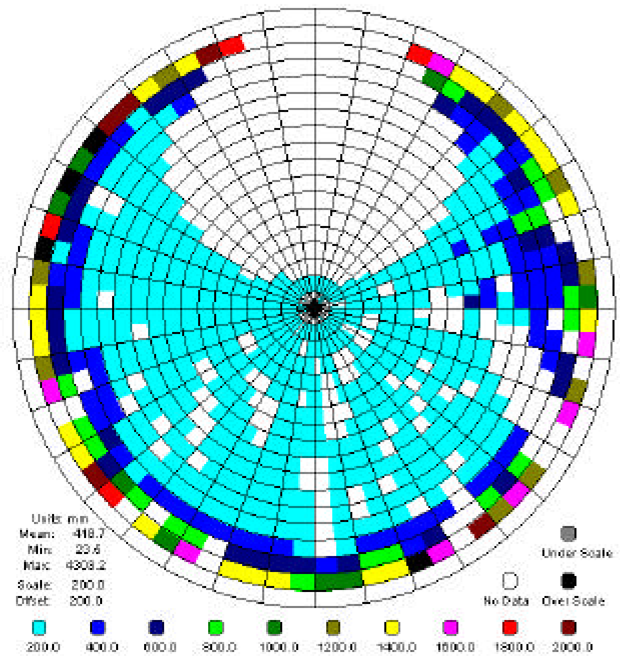

Figure 11. *L2 multipath in mm for 12-arm L1/L2 antenna*

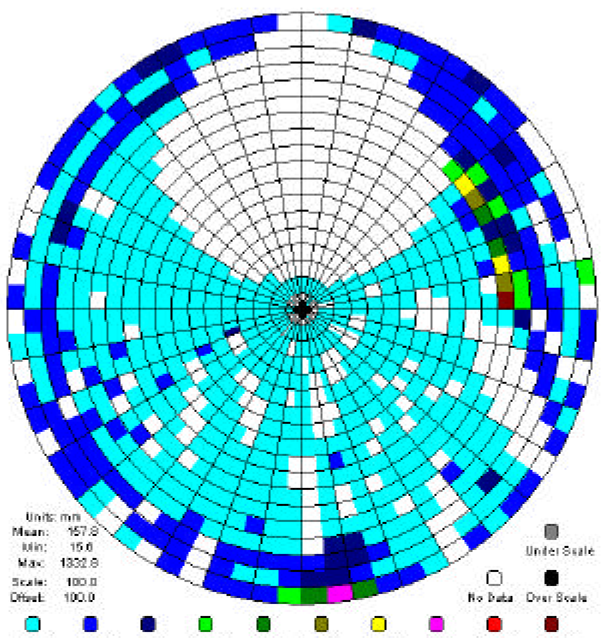

Figure 10. *L1 multipath in mm for choke ring antenna*

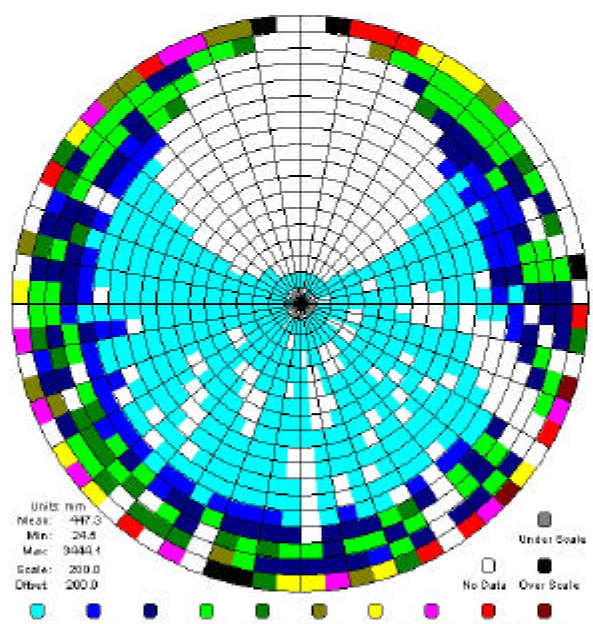

Figure 12. *L2 multipath in mm for choke ring antenna*

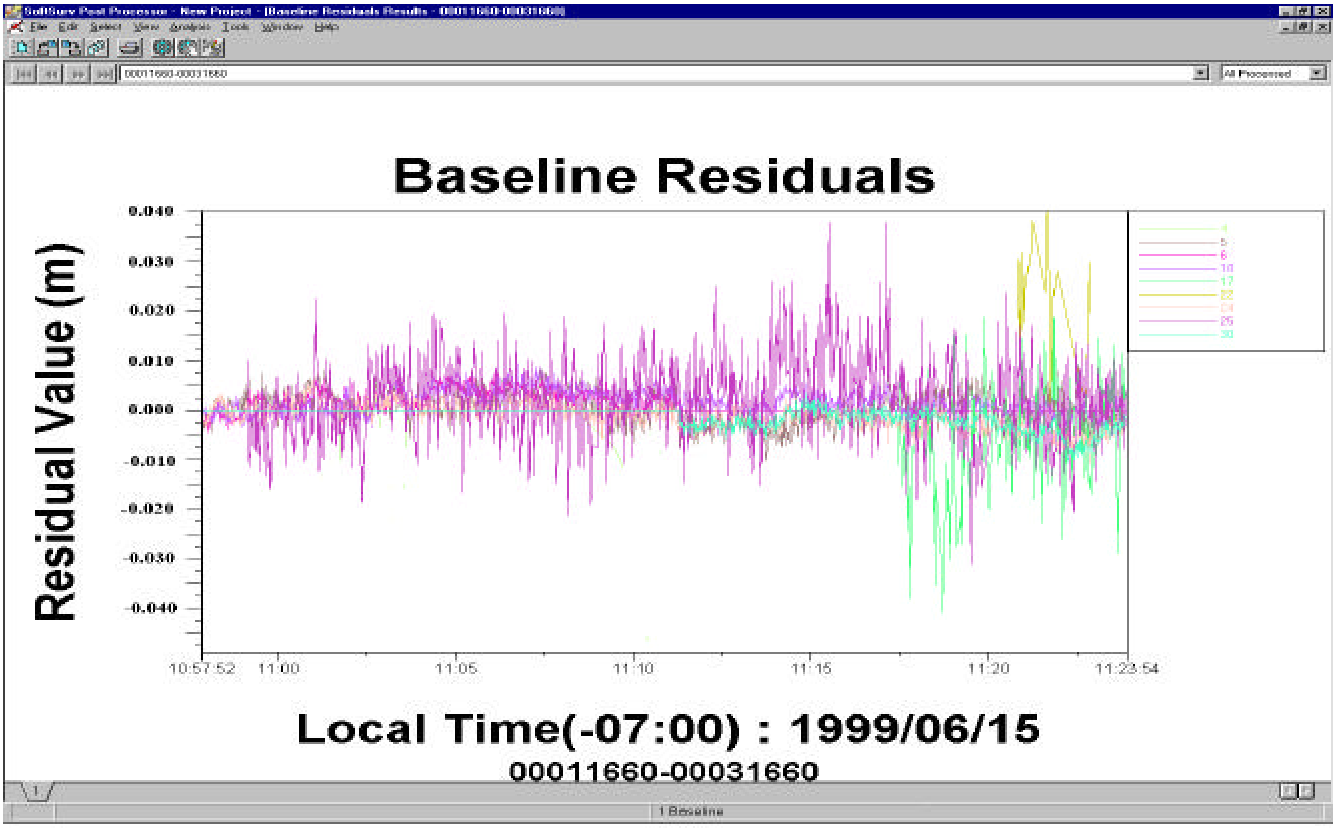

Figure 13. Baseline Residuals measured with 8-arm L1/L2 prototype antennas

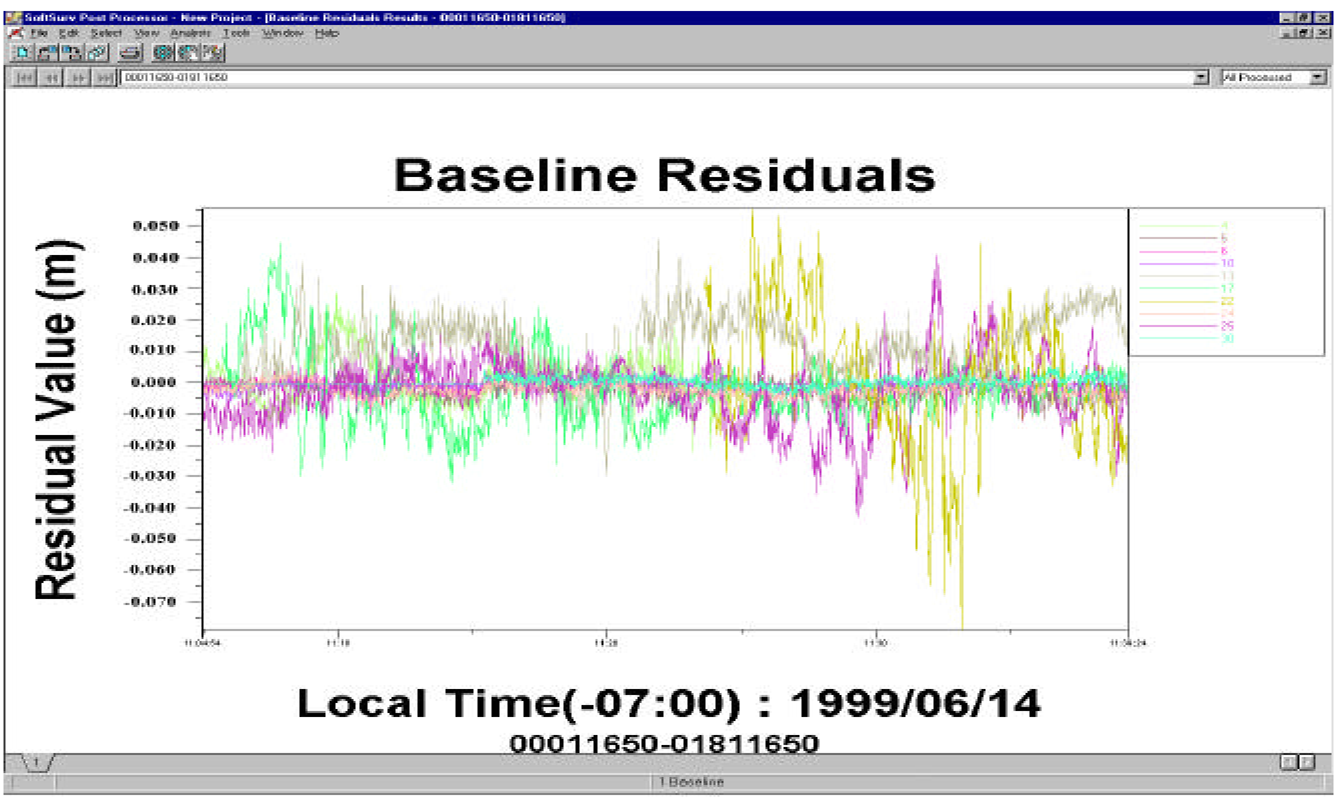

Figure 14. Baseline Residuals measured with high performance L1/L2 patch antenna

The typical peak-to-peak Baseline Residual variation is only ±10mm for pinwheel antennas as compared to ±20mm for patch antennas. Since there is no DC offset or scalloping effects with pinwheel antennas, data can be further filtered to yield even more precise baseline measurement.

CONCLUSIONS

A promising, patent pending, new technology has been applied to develop a novel GPS survey antenna. This antenna offers a performance similar to one achieved with a "choke ring" antenna, however with much reduced size and weight.

The antenna performance described in this paper makes it very suitable for very long baseline applications such as "tectonic plate movement monitoring", telescope alignment in "deep space monitoring project", or seismic surveying.

The low profile of the antenna makes it suitable for other applications such as vehicle, aircraft, missile/rocket and manpack applications.

The antenna was designed to meet harsh environment requirements, making it also suitable for marine and arctic applications.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance and help provided during this antenna research and development by Mike Blarowski, David Plamondon and Dana Hynes. The financial support provided by NovAtel Inc. and Canadian Research Council to fund this project is also greatly appreciated.

Antennas

GPS-704-X

Dual Frequency Antenna Delivers Excellent Performance, Multipath Rejection and L-band Functionality

Benefits

Provides a single antenna solution for GPS L1, L2, L5, Galileo L1, E5a & b, E6, GLONASS L1, L2 and L-band

Features

Access to multiple Global Navigation Satellite Systems

Exceptional L-band Reception

The GPS-704-X Galileo passive antenna features improved performance to ensure excellent operation in all GPS, Galileo and GLONASS frequency bands. The antenna also includes NovAtel's patented Pinwheel ™ technology for excellent multipath rejection and phase centre stability.

If you require more information about our antennas, visit novatel.com/products/gnss-antennas

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China 0086-21-54452990-8011

Europe 44-1993-848-736

SE Asia and Australia 61-400-883-601

Performance

3 dB Pass Band	**1.15 - 1.65 GHz**
Passive Antenna	External LNA Required

Gain at Zenith (90°)

L1	+6.0 dBic (minimum)
L2	+2.5 dBic (minimum)
L5, E5a	+2.0 dBic (minimum)
E6	+3.0 dBic (minimum)
L-band	+6.0 dBic (minimum)

Gain Roll-Off (from Zenith to Horizon)

L1, L-band	14 dB
L2, E6	11 dB
L5,E5	11 dB
VSWR	≤ 2.0 : 1
Nominal Impedance	50 Ω
Altitude	9,000 m

Physical and Electrical

Size

Diameter[1]	185 mm
Height	69 mm
Weight	468 g
Connector	TNC female

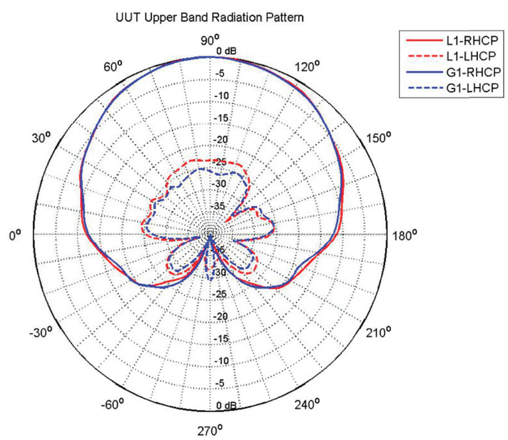
Environmental

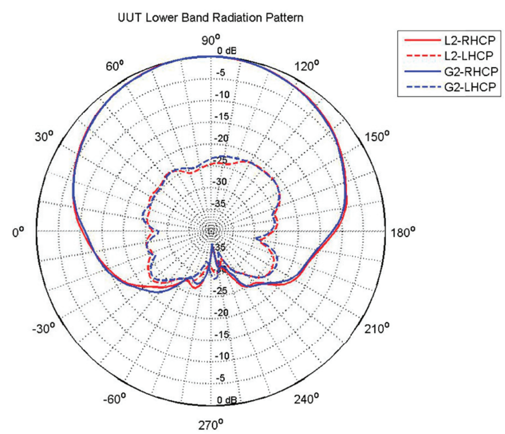
Temperature

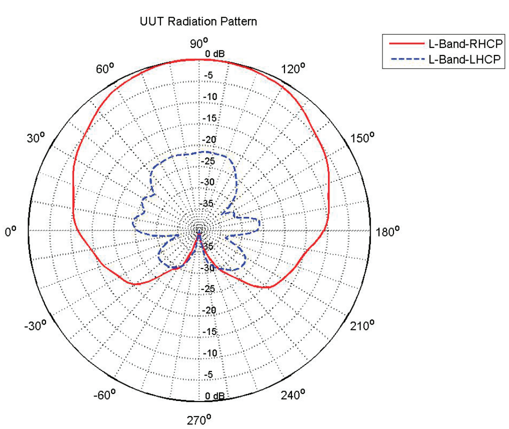
Operating	-40°C to +85°C
Storage	-55°C to +85°C
Humidity	95% non-condensing
Salt Spray	MIL-STD-810F, 509.4
Ingress Protection	IPX6 and IPX7
Waterproof	IEC 60529 IPX7
Compliance	CE
RoHS	EU Directive 2002/95/EC

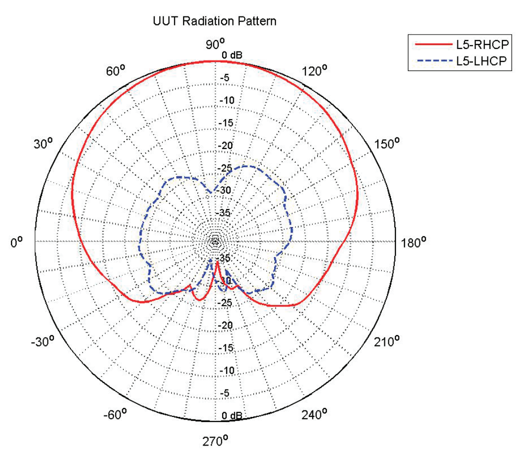
Elevation Gain Patterns

These plots represent the typical right-hand polarized (RHP) and left-hand polarized (LHP) normalized radiation patterns for the L1 frequency, the L2 frequency, the L-band and the L5 frequency, respectively.









Version 3 -Specifications subject to change without notice.

Printed in Canada. D09449
GPS-704-X September 2011
For the most recent details of this product:
novatel.com/Documents/Papers/GPS-704-X.pdf

[1] Not including tape measure tab. Full diameter with tape measure tab is 195 mm.

L-band Antenna Performance Improvements

NovAtel Inc.

ABSTRACT

NovAtel's GPS-702L provides combined L1/L2 and L-band reception in a single antenna. Designed for use with the OmniSTAR and Canada-wide Differential GPS (CDGPS) correction services, the GPS-702L is a replacement for NovAtel's GPS-600-LB antenna. The difference of the GPS-702L over its predecessor is its ability to improve on RTK while maintaining L-band performance.

The performance of the GPS-702L, both on its own and as compared to the GPS-702 and the GPS-600-LB, was evaluated by collecting system level measurements under a variety of conditions. Three of the tests were designed to simulate typical applications in which the GPS-702L is often used. The first is a high multipath environment. The second is driving back and forth with 180-degree turns, as encountered in precision agriculture applications. Thirdly, the ambiguity resolution time, important for RTK applications, was assessed. To complete the analysis, the antenna gain patterns and phase centre variations were plotted.

The test results collected show that the GPS-702L offers comparable performance to the GPS-702 and consistently outperforms its predecessor, the GPS-600-LB. As a result, the GPS-702L is considered an ideal solution for high precision, real-time applications using L-band technology and for users who operate in both L-band and RTK modes with a single antenna.

ANTENNA OVERVIEW

NovAtel's GPS-702L, part of NovAtel's GPS-700 antenna series, offers access to the GPS L1 and L2 frequencies, as well as the L-band frequencies used by the OmniSTAR and Canada-wide Differential GPS (CDGPS) correction services.

Figure 1 – GPS-702L Antenna

When combined with NovAtel's ProPak-LB*plus* receiver, the GPS-702L allows users to take advantage of the improved positioning accuracy provided by L-band technology. For users within North America, free CDGPS L-band corrections provide sub-meter accuracy with a data signal structured to perform well in difficult conditions such as heavy foliage. Worldwide, OmniSTAR's subscription-based service offers real-time DGPS positioning with meter- to decimeter-level accuracy.

Figure 2 – ProPak-LB*plus* Receiver

Features and Benefits

In addition to superior L1, L2, and L-band reception, the GPS-702L features improved RTK performance for high-accuracy, real-time positioning applications. Closely located L1 and L2 phase centers combined with high phase center stability ensure optimal RTK operation, even over long baselines.

In addition, the GPS-702L meets the European Union's directive for Restriction of Hazardous Substances (RoHS). As one of the first RoHS compliant GPS products, integrators can be confident that the GPS-702L can be used in system designs for years to come.

For extended life, the GPS-702L also features a waterproof housing and meets the vibration and salt spray standards as shown in *Table 3* on *Page 2*. Sharing the same form factor as the other antennas in the GPS-700 series, the GPS-702L is compact and lightweight, making it a highly portable and rugged antenna suitable for a wide variety of environments and applications.

Pinwheel Technology

The GPS-702L features NovAtel's patented Pinwheel technology with its aperture coupled slot array design. This unique configuration offers superior amplitude radiation pattern roll-off near the horizon, in effect eliminating multipath-generated replicas of the original line-of-sight (LOS) signal. It also exhibits excellent sensitivity to right-hand circularly polarized signals over a wide range of elevations and in all azimuth directions. The Pinwheel design results in an excellent axial ratio as well, ensuring that a high quality signal is received. It also provides enhanced immunity against EMC/EMI and electromagnetic pulse interference.

Specifications

Specifications for the GPS-702L antenna are provided in the tables that follow.

Table 1 – GPS-702L Performance Specifications

Pass Band	
L1 (3 dB)	1575 ± 20 MHz (typical)
L2 (3 dB)	1228 ± 20 MHz (typical)
L-band (1 dB)	1543 ± 20 MHz (typical)
Out-of-Band Rejection	
L1, L-band	
1555 ± 75 MHz	30 dBc (typical)
1555 ± 100 MHz	50 dBc (typical)
L2	
1227 + 50 MHz	25 dBc (typical)
1227 - 50 MHz	30 dBc (typical)
1227 ± 100 MHz	50 dBc (typical)
LNA Gain	27 dB (typical)
Gain at Zenith (90°)	
L1	+5.0 dBic (minimum)
L2	+1.5 dBic (minimum)
L-band	+5.0 dBic (minimum)
Gain Roll-Off [1]	
L1	13 dB
L2	12 dB
L-band	13 dB
Noise Figure	≤ 2.5 dB (typical)
VSWR	≤ 2.0 : 1
L1-L2 Differential Propagation Delay	15 ns (maximum)
Nominal Impedance	50 Ω
Altitude	9,000 m

[1] From zenith to horizon.

Table 2 – GPS-702L Physical and Electrical Specifications

Diameter[2]	185 mm
Height	69 mm
Weight	500 g
Input Voltage	+4.5 to +18 VDC
Current Consumption	33 mA (typical)
Connector	TNC female
Regulatory	FCC Class B, CE

Table 3 – GPS-702L Environmental Specifications

Operating Temperature	-40°C to +85°C
Storage Temperature	-55°C to +85°C
Humidity	95% non-condensing
Random Vibration	MIL-STD-810F, 514.5, 7.706
Sinusoidal Vibration	ASAE 5.15.2, Level 1
Shock	IEC 68-2-27, Ea
Bump	IEC 68-2-29, Eb
Salt Spray	MIL-STD-810F, 509.4
Waterproof	IEC 60529 IPX7
RoHS	EU Directive 2002/95/EC

TESTING OVERVIEW

To evaluate the performance of the GPS-702L, a variety of measurements were taken:

- Code minus carrier standard deviation under high multipath conditions
- L-band signal to noise ratio during 180-degree turns
- Percentage of ambiguity resolutions over time after an RTK reset
- Antenna gain over elevation and azimuth
- Phase centre variations

For comparison, the same data was collected for the GPS-702, NovAtel's L1/L2 antenna, and the GPS-600-LB, the predecessor to the GPS-702L. Where applicable, the antennas were connected to receivers of identical model, software load, and configuration.

TEST RESULTS

Multipath Performance

To gauge an antenna's resistance to multipath, the amount of variation in the code minus carrier measurement can be examined. As the pseudorange code is much more susceptible to noise than the carrier, when the difference between the two is taken,

[2] Not including tape measure tab. Full diameter with tape measure tab is 195 mm.

what remains is largely the noise found on the code. Large variations in the code noise can typically be attributed to multipath. As a result, the multipath susceptibility of an antenna can be shown by plotting the standard deviation of the code minus carrier.

To evaluate the multipath performance of the GPS-702L, GPS-702, and GPS-600-LB, the antennas were placed on the edge of the roof at the NovAtel offices, a high multipath environment. Each antenna was connected to an identical receiver and the code minus carrier standard deviations at various satellite elevations were calculated. The data for all three antennas is shown for the L1 and L2 frequencies in *Figure* 3 and *Figure 4*, respectively.

Figure 3 - L1 Code Minus Carrier Standard Deviation vs Satellite Elevation

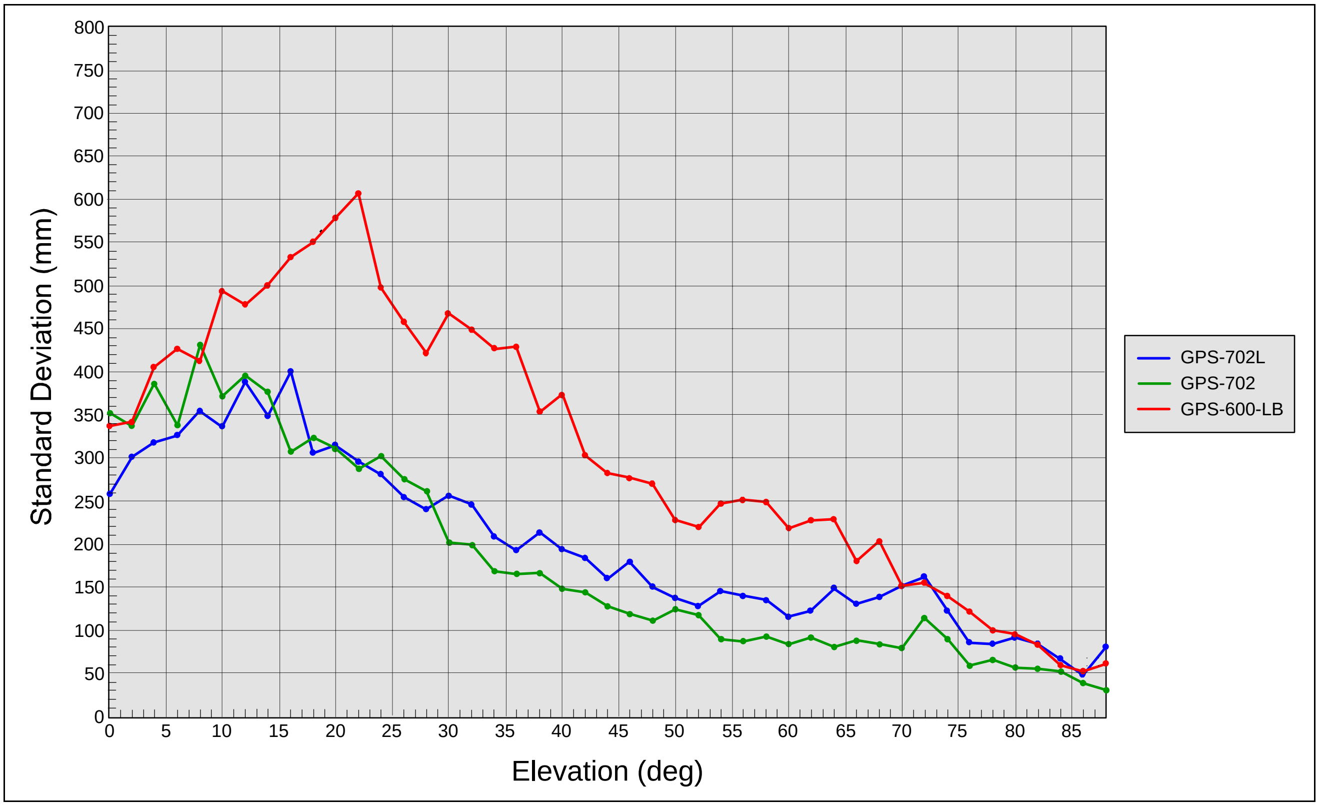
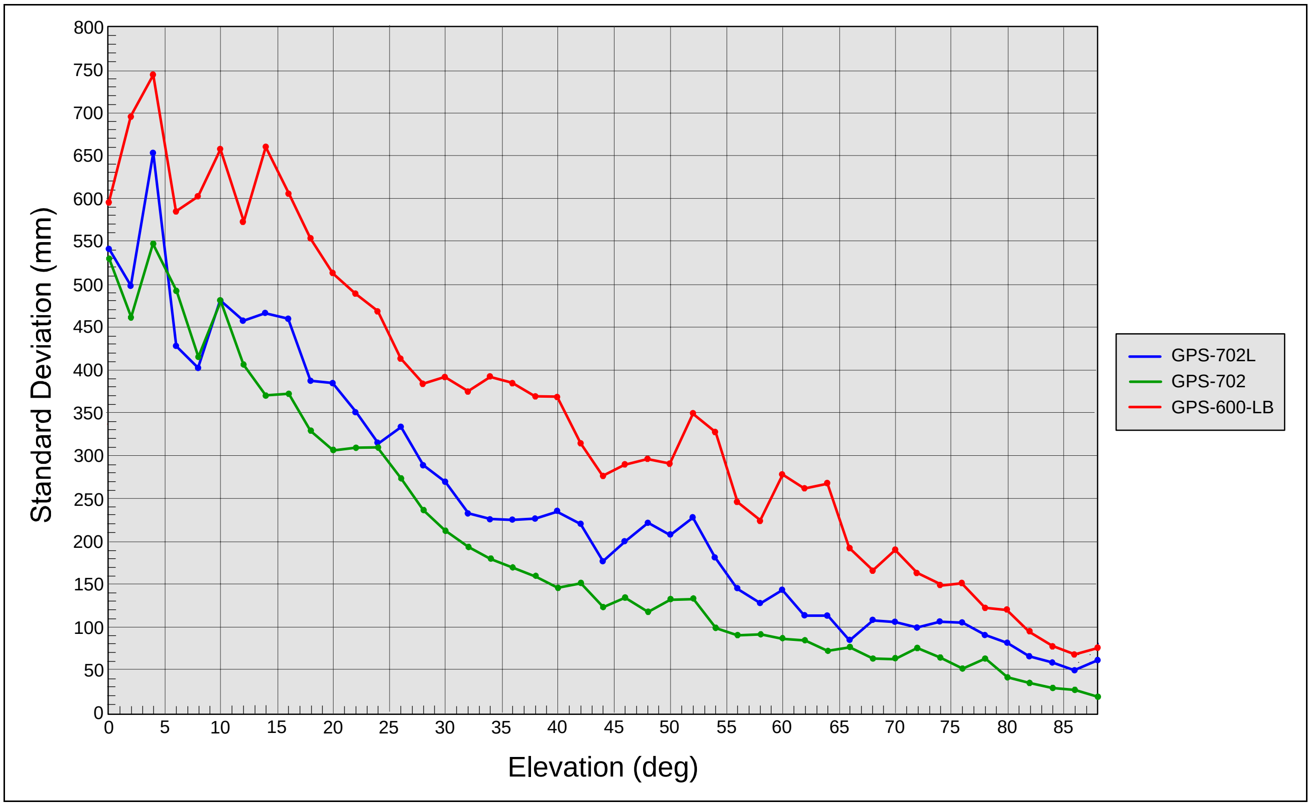


Figure 4 – L2 Code Minus Carrier Standard Deviation vs Satellite Elevation

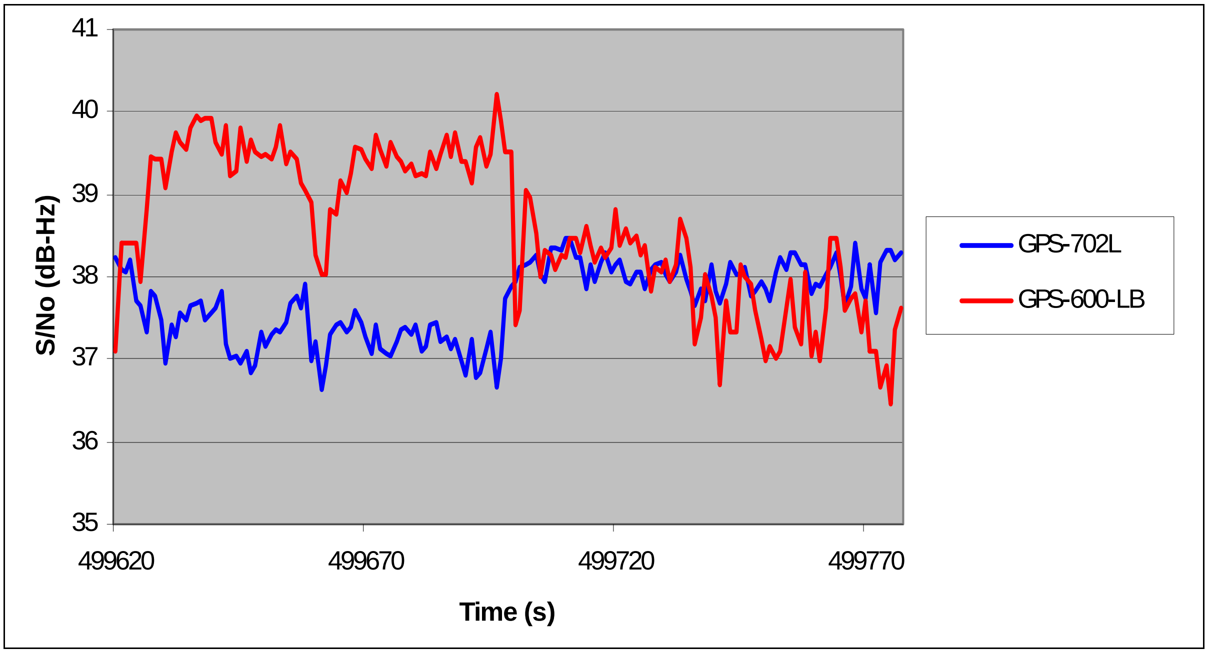


As can be seen from the plots, the GPS-702L shows similar high resistance to multipath as the GPS-702. The GPS-600-LB shows increased variation in the code minus carrier measurement, particularly at satellite elevations below 40 degrees, making it less ideal for high multipath areas.

Stability during Turns

L-band technology is often used in precision agriculture to provide improved accuracy without the need for a separate base station. Typically, agricultural equipment, along with the positioning system, travels up and down the field, with 180-degree turns at each end of the field. To assess antenna performance in this type of application, L-band signal to noise data was collected from side by side GPS-702L and GPS-600-LB antennas during a series of 180-degree turns. The data during a single turn is shown in *Figure 5*.

Figure 5 – L-band Signal to Noise Ratio for a Single 180-Degree Turn



As expected by the design, overall the GPS-702L L-band signal to noise is slightly lower than the GPS-600-LB. However, the GPS-702L shows less variation as the antenna turns 180 degrees, at approximately 499695 seconds. This is supported by the larger variation in azimuth that the GPS-600-LB exhibits, as detailed in the section entitled *Antenna Gain Pattern*.

Resolution Time

Antenna quality can also affect the amount of time required for ambiguity resolution. A GPS-702L, GPS-702, and GPS-600-LB were set up on the edge of the roof at the NovAtel offices and connected to identical receivers. For each antenna, the percentage of narrowlane ambiguities resolved by the receiver at various intervals since RTK reset was measured. The results are shown in *Figure 6*.

Figure 6 - Percentage of Narrowlane Ambiguity Resolutions over Time

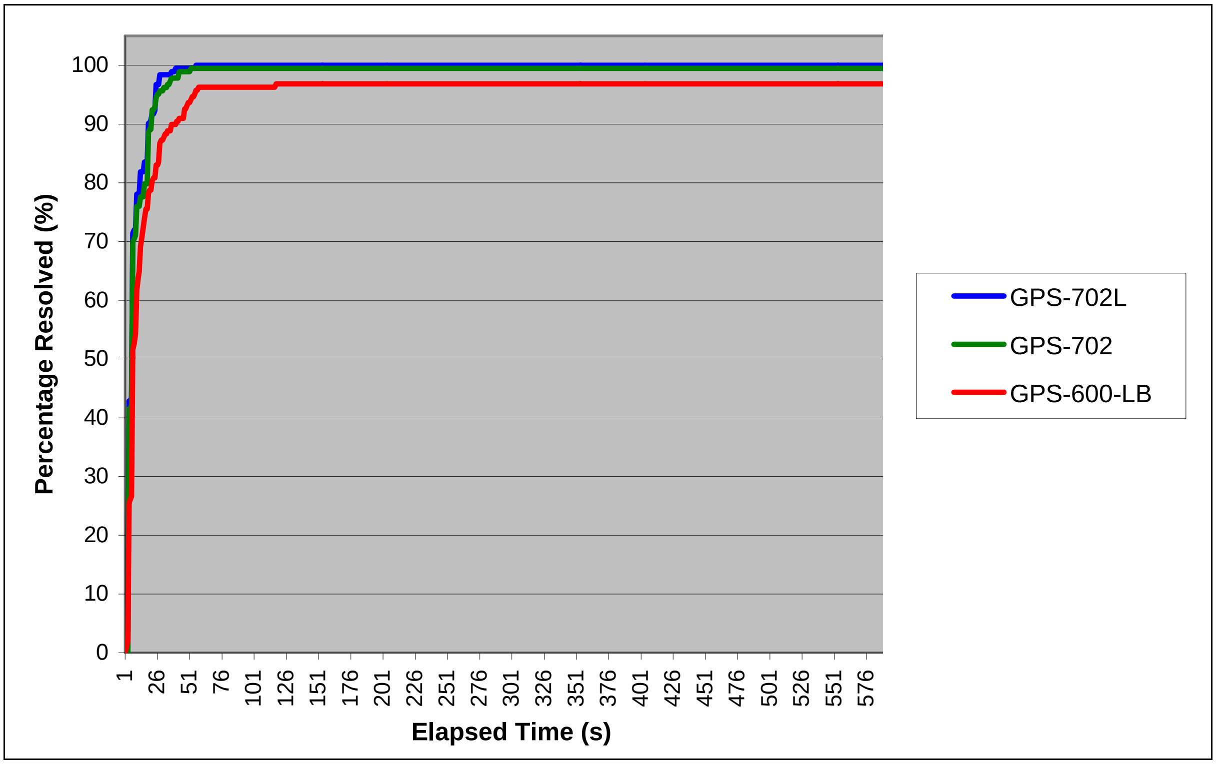
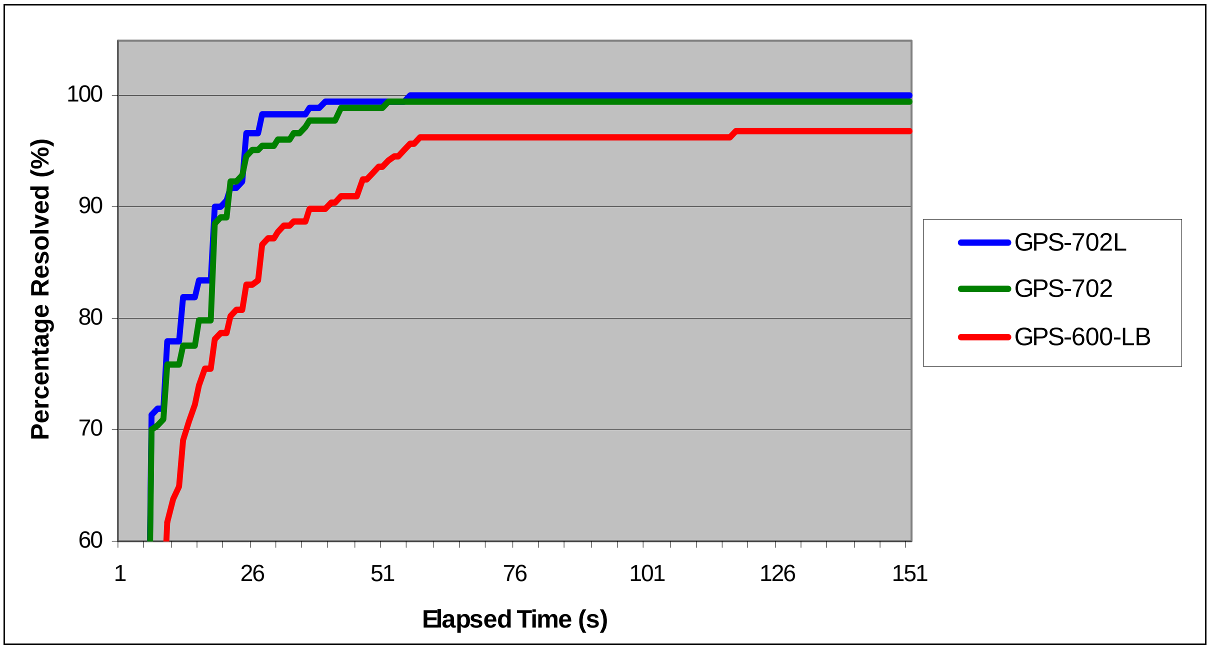


Table 4 shows the same data, but for a selection of time intervals from RTK reset. *Figure 7* that follows provides an enlarged view of a section of the previous plot, highlighting the main area of divergence between the antennas.

Table 4 - Percentage of Narrowlane Ambiguity Resolutions at Various Intervals

Time Since Reset (s)	% Resolved		
	GPS-702L	GPS-702	GPS-600-LB
5	43.407	42.077	26.596
10	78.022	75.956	63.830
30	98.352	96.175	87.766
60	100	99.454	96.277
120	100	99.454	96.809
180	100	99.4536	96.8085
300	100	99.4536	96.8085

Figure 7 - Percentage of Narrowlane Ambiguity Resolutions over Time (Zoomed-In View)



It is clear from the data that similar resolution time can be expected when using the GPS-702L as when using the GPS-702. The plots also show that both antennas outperform the GPS-600-LB. As an example, at 25 seconds from RTK reset, the receiver using the GPS-702L shows approximately 14 percent additional ambiguity resolutions over the identical receiver using the GPS-600-LB.

This difference can be attributed to better antenna performance offered by the GPS-702 and GPS-702L over the GPS-600-LB. A key benefit of the improved resolution time shown by the GPS-702L over the GPS-600-LB is the shorter time needed to reacquire a solution after the position is lost.

In looking at the percentages listed after the 120-second mark for the GPS-702 and GPS-600-LB antennas, it should be noted that the remainder of narrowlane solutions for these receivers were not resolved. This is likely a result of a test tool error as all three antennas tracked well during the test.

Antenna Gain Pattern

To further analyze the characteristics of the GPS-702L, the antenna gain pattern was plotted. The gain pattern is a graphical depiction of the relative field strength received by the antenna in relation to the elevation angle of the satellite transmitting the signal.

The gain patterns for the GPS-702L, GPS-600-LB, and GPS-702 follow. The gain for both right-hand polarized signals, which includes GPS signals, and left-hand polarized signals, such as direct multipath reflections, are included. For ease of use, the plots are normalized to the maximum graph value, 0 dB, and the peak gain value is listed next to each plot.

Figure 8 - GPS-702L Gain Pattern

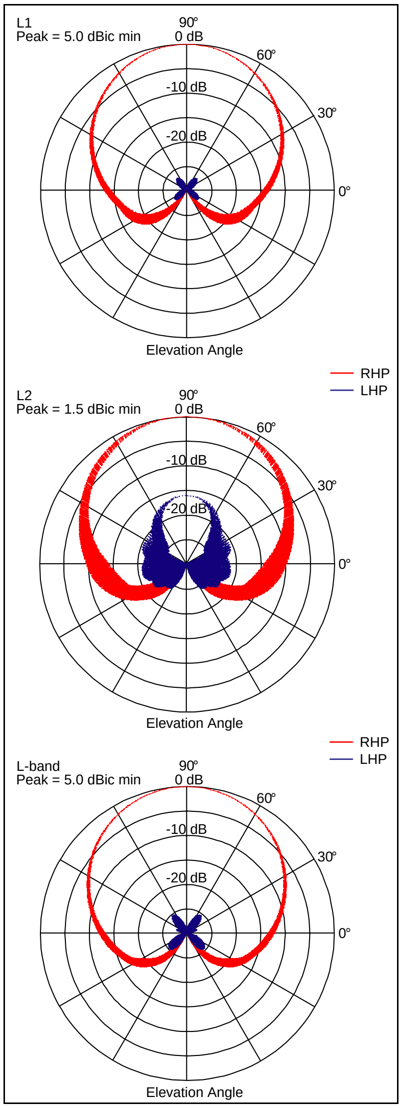


Figure 9 - GPS-600-LB Gain Pattern

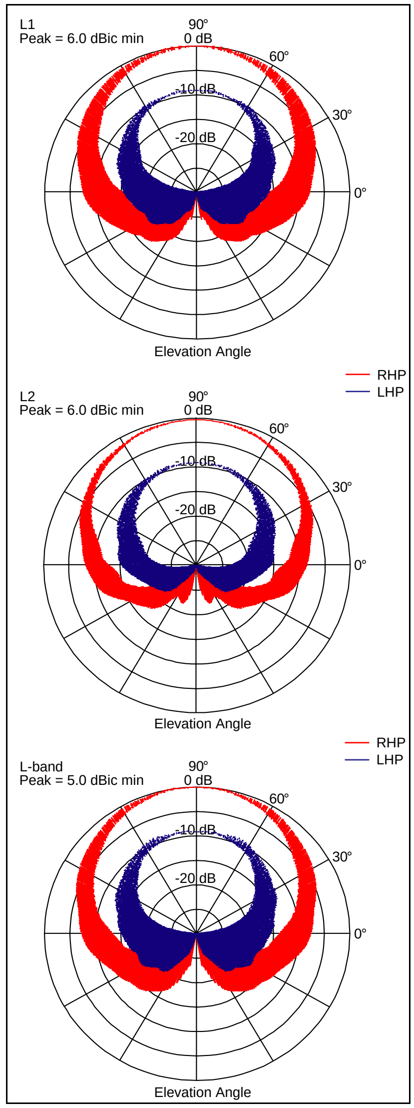
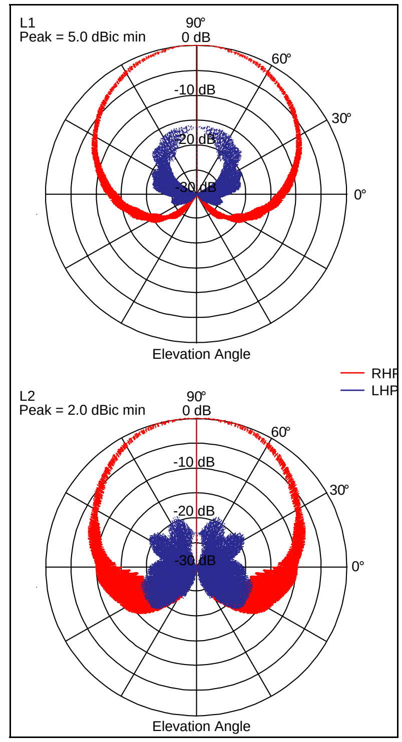


Figure 10 - GPS-702 Gain Pattern



On its own, the GPS-702L gain pattern shows the antenna has excellent multipath immunity. The limited gain for left-hand polarized signals ensures reception of direct reflections is minimized. The amplitude roll-off from peak elevation to 0º is between 12 dB and 13 dB, which compares well with a patch antenna mounted on a choke ring ground plane.

The thickness of the pattern's "line" indicates the amount of variation in gain in the azimuth plane. The GPS-702L shows minimal variation, largely less than 1 dB, especially for the L1 and L-band frequencies. A large variation in azimuth can potentially lead to biases in the range measurements that are difficult to compensate for.

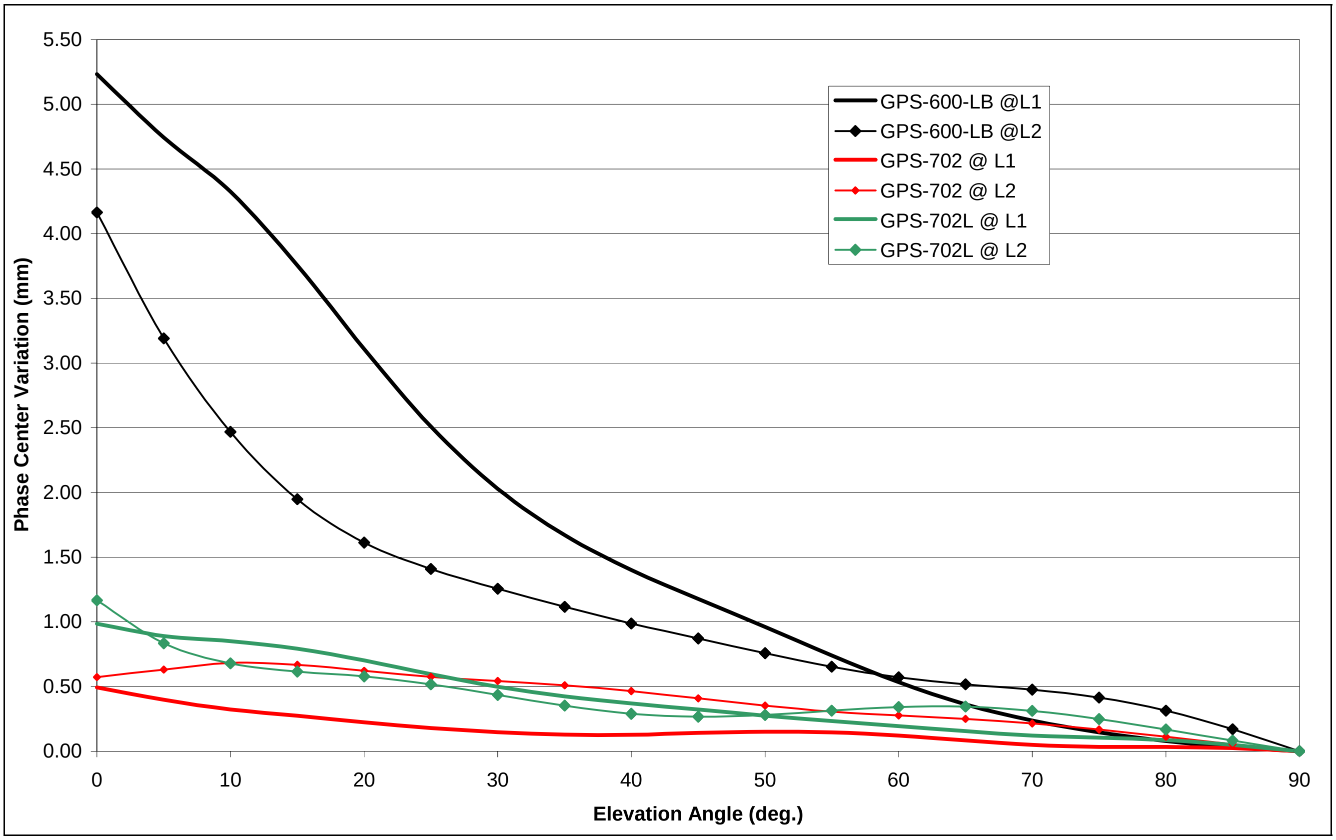
Compared to the GPS-600-LB, the gain pattern shows the GPS-702L to be superior. Left-hand polarized signals are minimized much more by the GPS-702L. Variation over azimuth is also reduced greatly.

When comparing the GPS-702L to the GPS-702, the gain pattern at the L1 and L2 frequencies is comparable, both showing excellent roll-off and minimization of left-hand polarized signals. Multipath detection in the GPS-702L is an improvement on the GPS-702 and much superior to the 600-LB at the L1 and L-Band frequencies.

Phase Centre Measurements

A summary of absolute antenna calibrations performed by Geo++ is shown in *Figure 11*. The elevation dependant absolute phase center variations (PCV) were determined for the GPS-600-LB, GPS-702 and GPS-702L antennas.

Figure 11 Phase Centre Variations



The figure shows that the GPS-702 antenna provides sub-millimeter PCV accuracy while GPS-702L provides millimeter level PCV accuracy. This provides much improved robustness for high accuracy mobile and static RTK applications when compared to the GPS-600-LB antenna.

SUMMARY

As seen from the data presented, NovAtel's GPS-702L antenna provides excellent performance and is an ideal solution for positioning systems requiring superior L-band reception. More specifically, the GPS-702L offers high multipath immunity and stability during turns and aids in quick ambiguity resolution for RTK applications.

The data also shows that the GPS-702L compares very well against the GPS-702, NovAtel's L1/L2 antenna, and consistently outperforms the GPS-600-LB, NovAtel's previous generation L1/L2/L-band antenna.

For more information on the GPS-702L, contact NovAtel at 1-800-NovAtel or 403-295-4900 or visit our website at www.novatel.com.

US006445354B1

(12) **United States Patent**
Kunysz

(10) **Patent No.: US 6,445,354 B1**
(45) **Date of Patent: *Sep. 3, 2002**

(54) **APERTURE COUPLED SLOT ARRAY ANTENNA**

(75) Inventor: **Waldemar Kunysz**, Calgary (CA)

(73) Assignee: **NovAtel, Inc.**, Calgary (CA)

(*) Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/375,319**

(22) Filed: **Aug. 16, 1999**

(51) **Int. Cl.**[7] **H01Q 13/10**
(52) **U.S. Cl.** **343/770**; 343/792.5; 343/895
(58) **Field of Search** .... 343/700 MS, 895, 343/767, 769, 770, 846, 829, 792.5, 853; H10Q 13/10

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,568,206 A	*	3/1971	Sisson	343/750
3,696,433 A	*	10/1972	Killion et al.	343/770
4,315,266 A		2/1982	Ellis, Jr.	343/895
4,477,814 A	*	10/1984	Brumbaugh et al.	343/725
4,525,720 A		6/1985	Corzine et al.	343/895
4,608,572 A	*	8/1986	Blakney et al.	343/792.5
4,658,262 A		4/1987	DuHamel	343/895
5,220,340 A		6/1993	Shafai	343/895
5,313,216 A		5/1994	Wang et al.	343/700 MS
5,402,136 A	*	3/1995	Goto et al.	343/729
5,451,973 A		9/1995	Walter et al.	343/895
5,621,422 A		4/1997	Wang	343/895
5,646,633 A		7/1997	Dahlberg	343/700 MS
5,712,647 A		1/1998	Shively	343/895
5,815,122 A		9/1998	Nurnberger et al.	343/767
5,861,848 A		1/1999	Iwasaki	343/700
5,936,594 A		8/1999	Yu et al.	343/895

OTHER PUBLICATIONS

Nurnberger, M. W. et al., "A New Planar Feed For Slot Spiral Antennas", IEEE Transactions On Antennas and Propagation, vol. 44, No. 1, 1996, pp. 130–131.

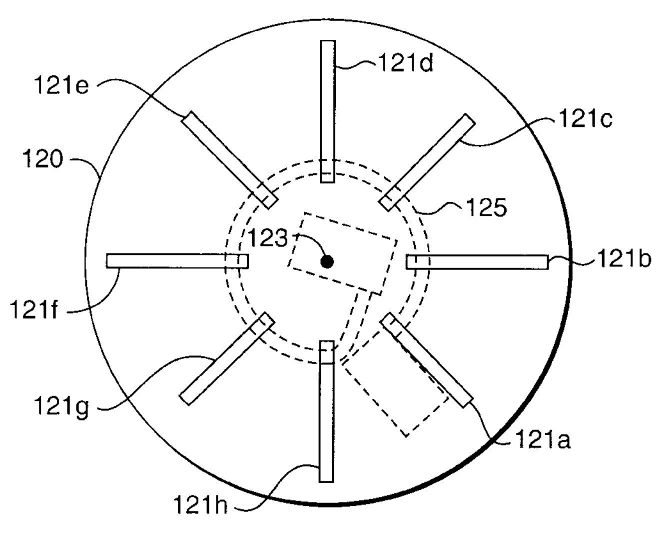
* cited by examiner

Primary Examiner—Tho Phan
(74) *Attorney, Agent, or Firm*—Cesari and McKenna, LLP

(57) **ABSTRACT**

A planar, phased-array antenna including a nonconductive substantially planar substrate and a transmission line disposed on one surface is disclosed, a segment of the transmission line forming an arc of radius R centered on the antenna axis. A conductive layer on the other antenna surface includes two or more slotted openings, each slotted opening having one end located within a distance R of the antenna axis, such that, when an electromagnetic signal is fed into one end of the transmission line, electromagnetic energy is sequentially coupled into the slotted openings, and a circularly-polarized signal is radiated from the antenna substantially in the direction of the antenna axis. An amplifier or a connector may be electrically connected to one or both ends of the transmission line, or one end of the transmission line may be terminated in an impedance load to form a leaky-wave antenna. The slotted openings may comprise either or both straight and curved segments, and may be of the same or unequal lengths. Curved slotted openings may be oriented clockwise or counter-clockwise to transmit or receive either is left-handed or right-handed polarized signals.

42 Claims, 7 Drawing Sheets



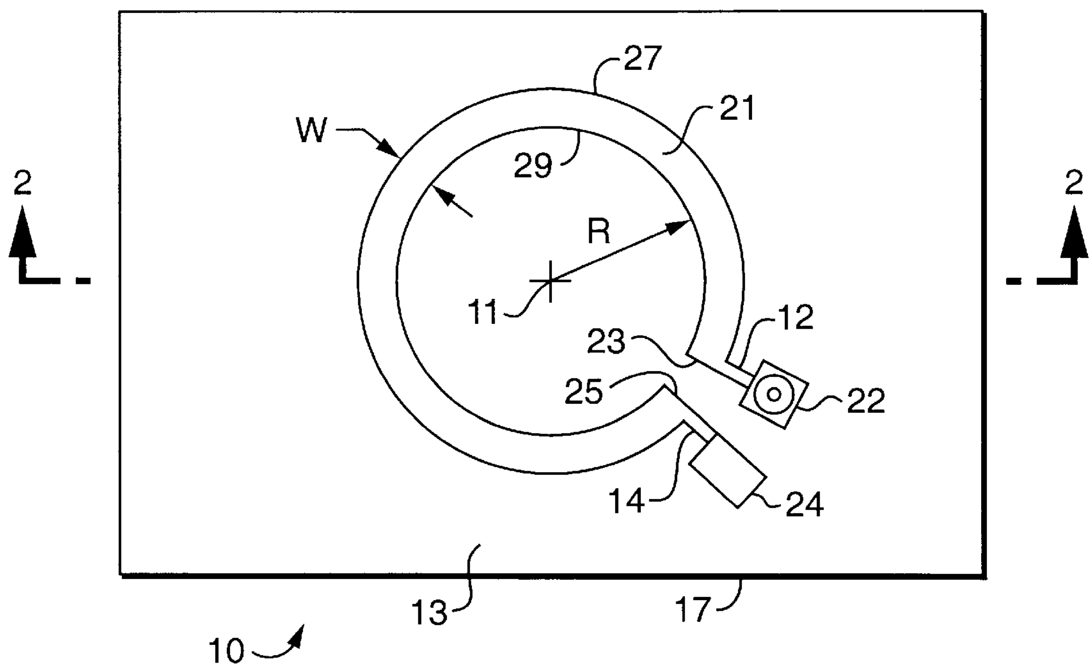


FIG. 1

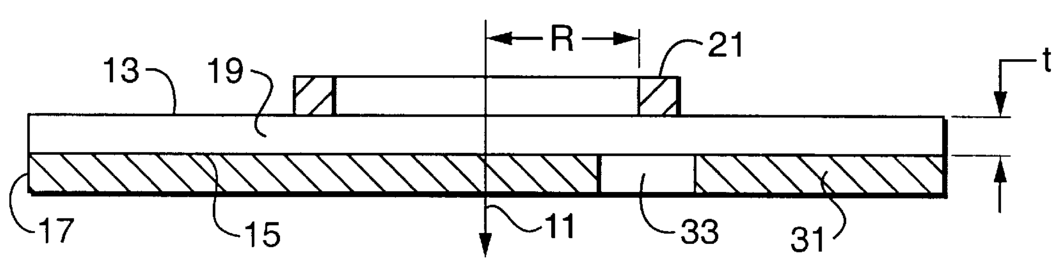
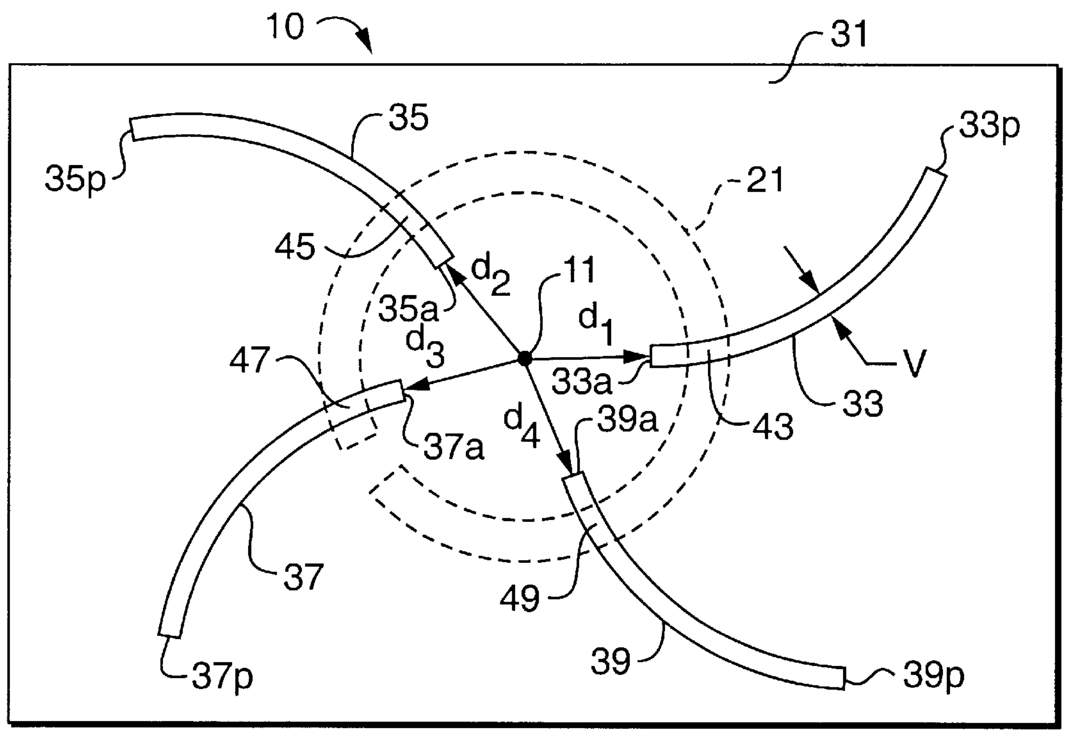


FIG. 2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31
35
33p
35p
21
45
d2
11
35a
d1
d3
47
33a
V
33
43
39a
d4
37a
37
49
39
37p
39p

FIG. 3

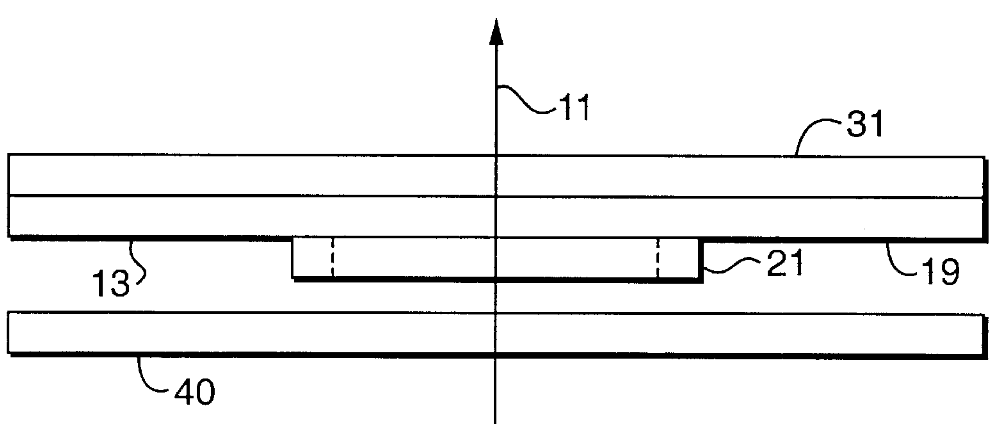
11
31
13
21
19
40

FIG. 4

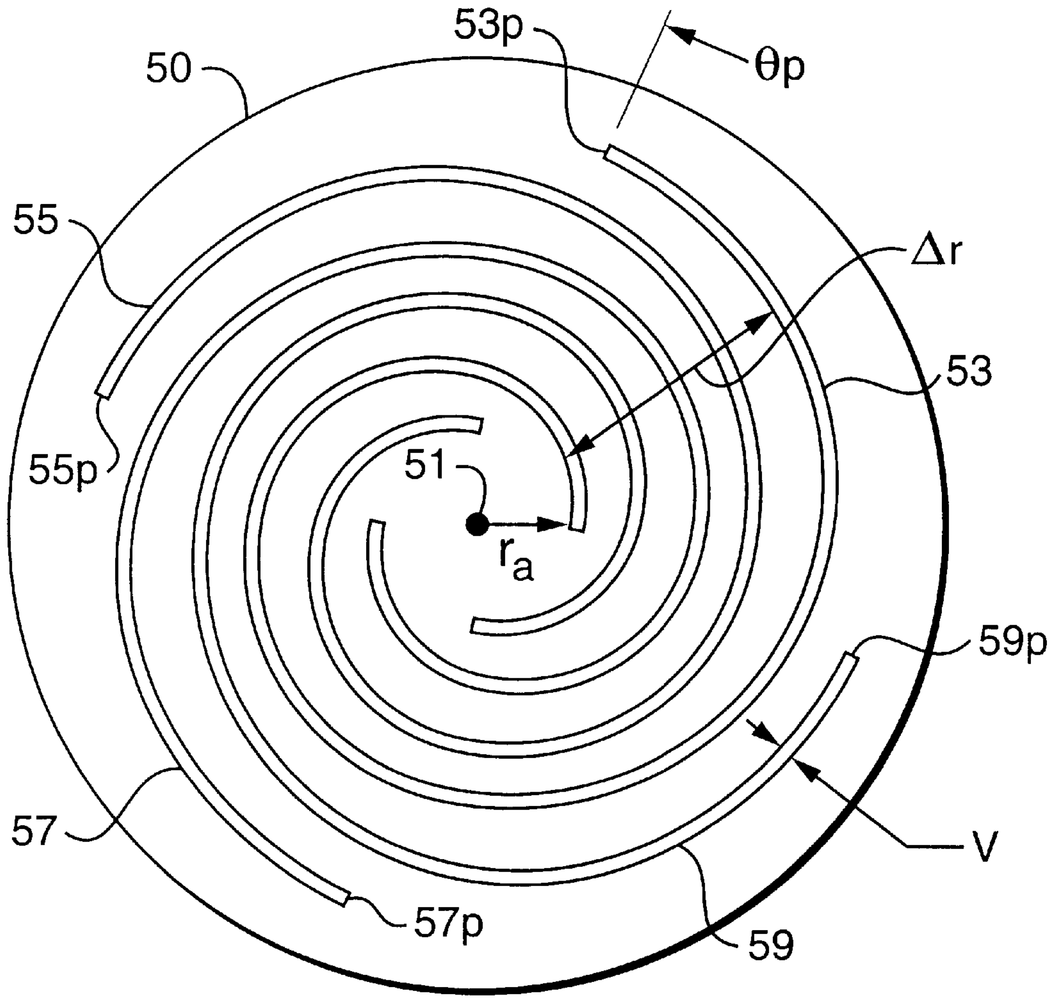

FIG. 5

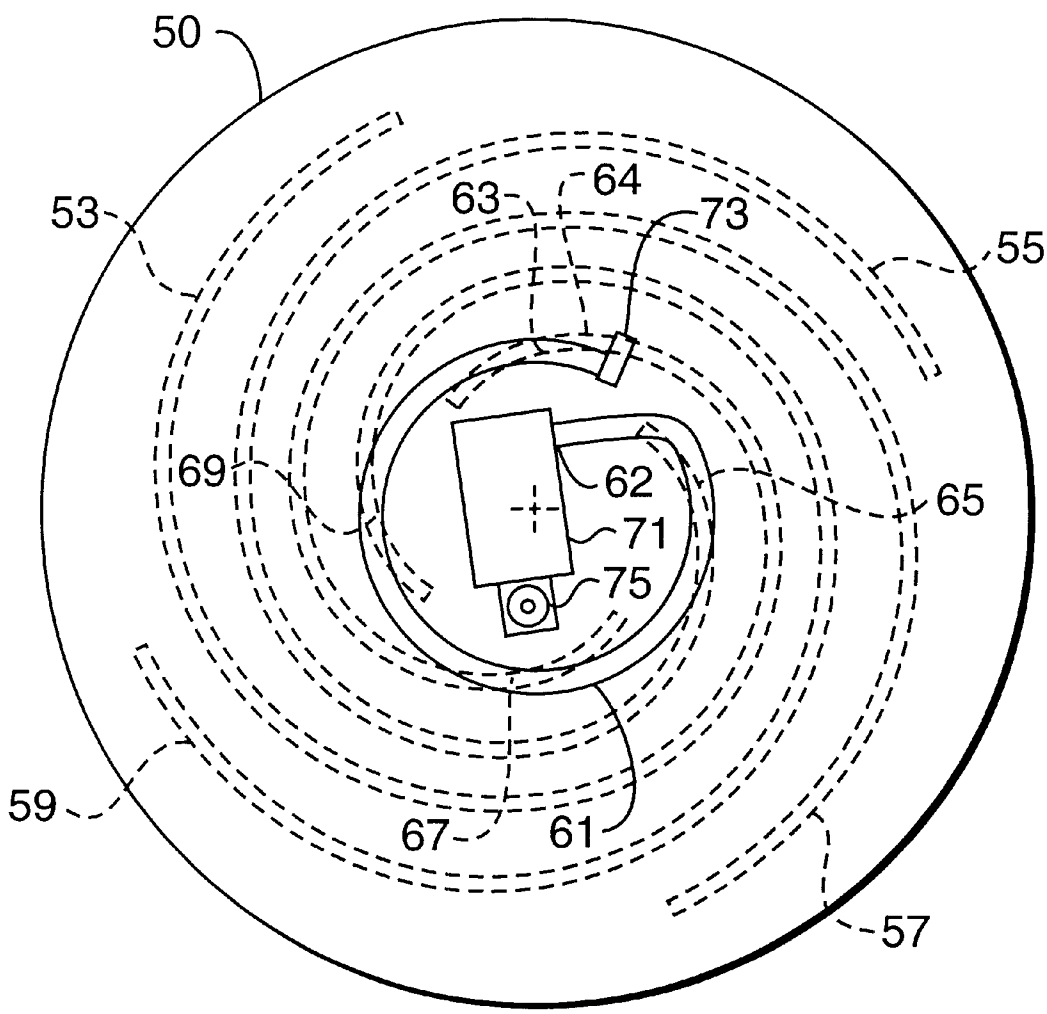

FIG. 6

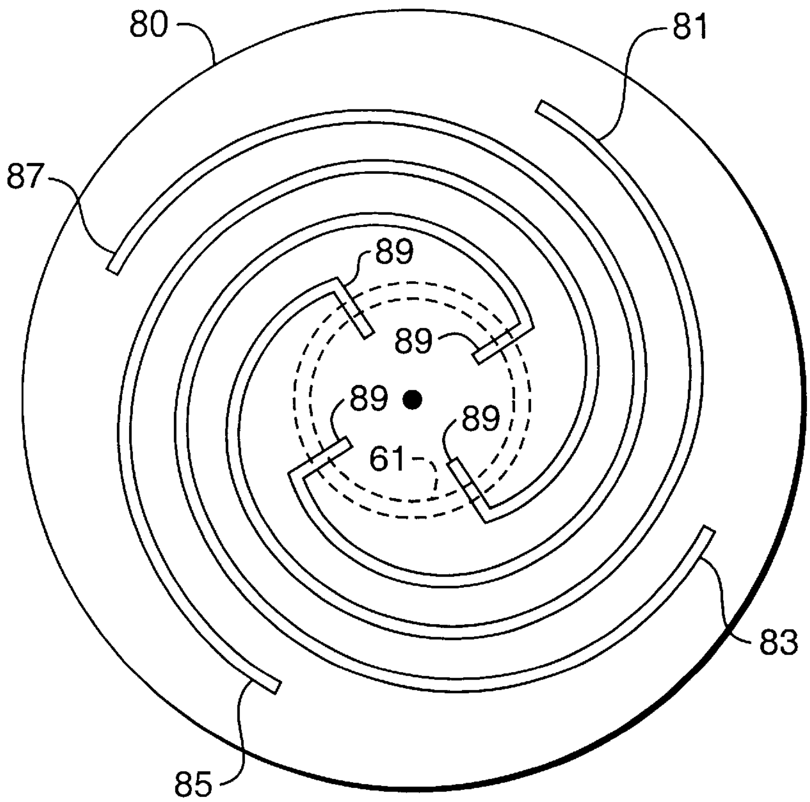

FIG. 7

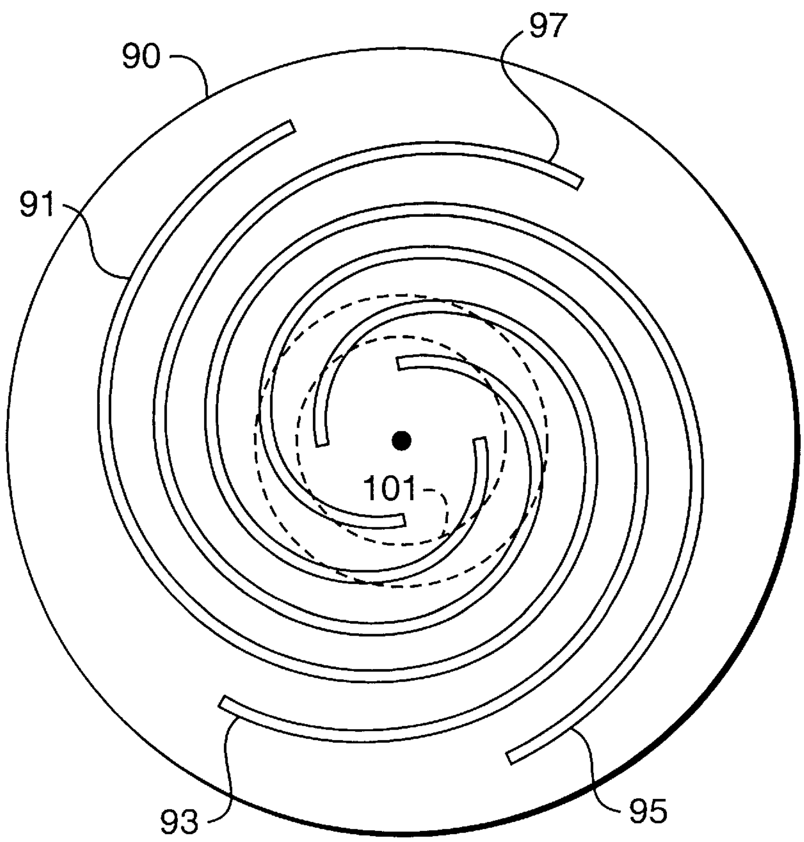

FIG. 8

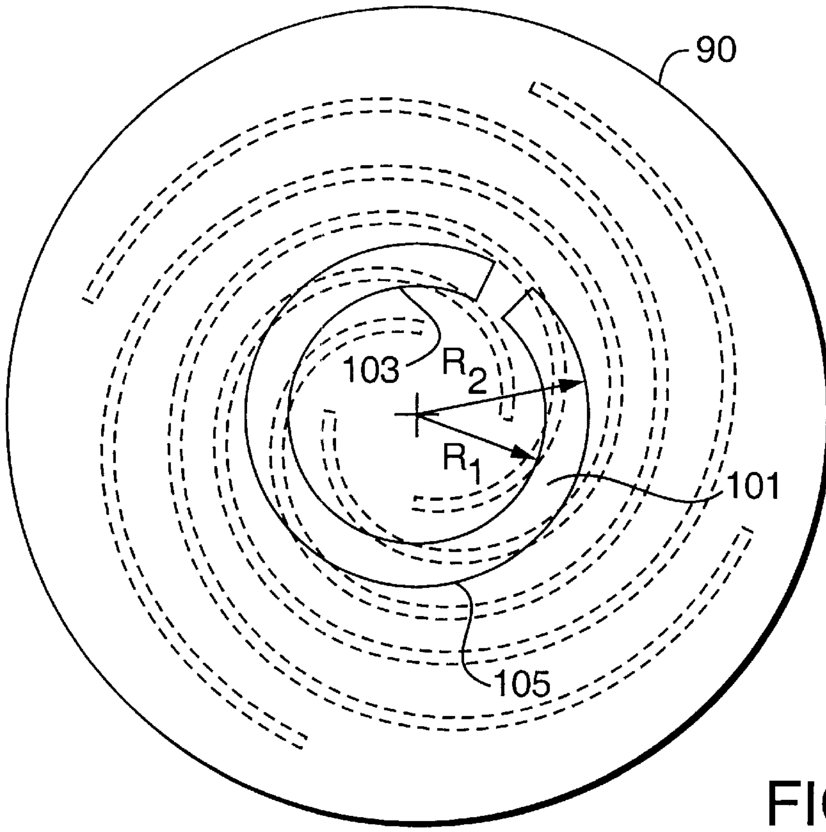

FIG. 9

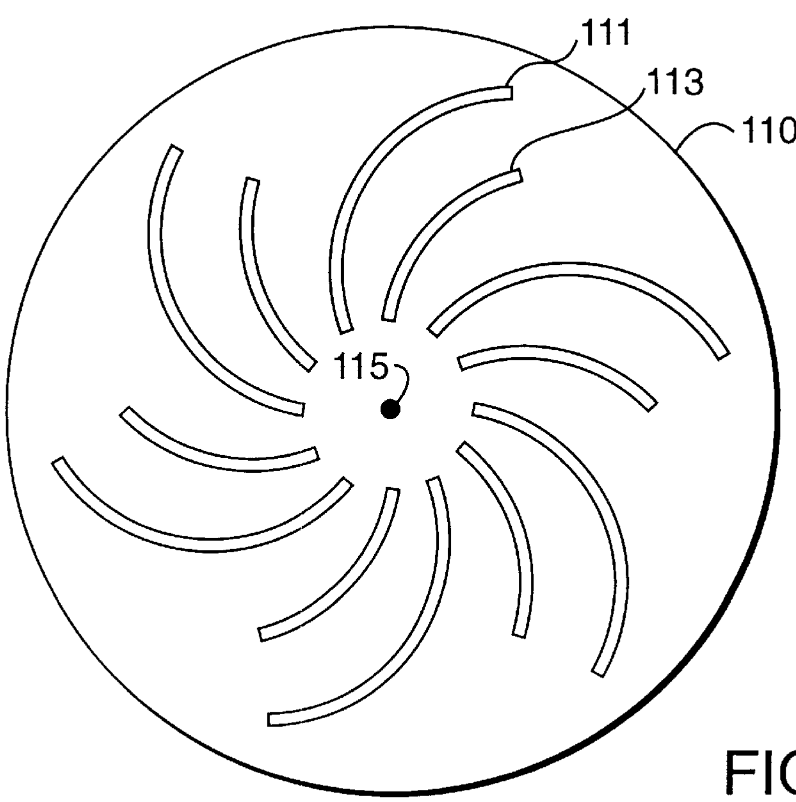

FIG. 10

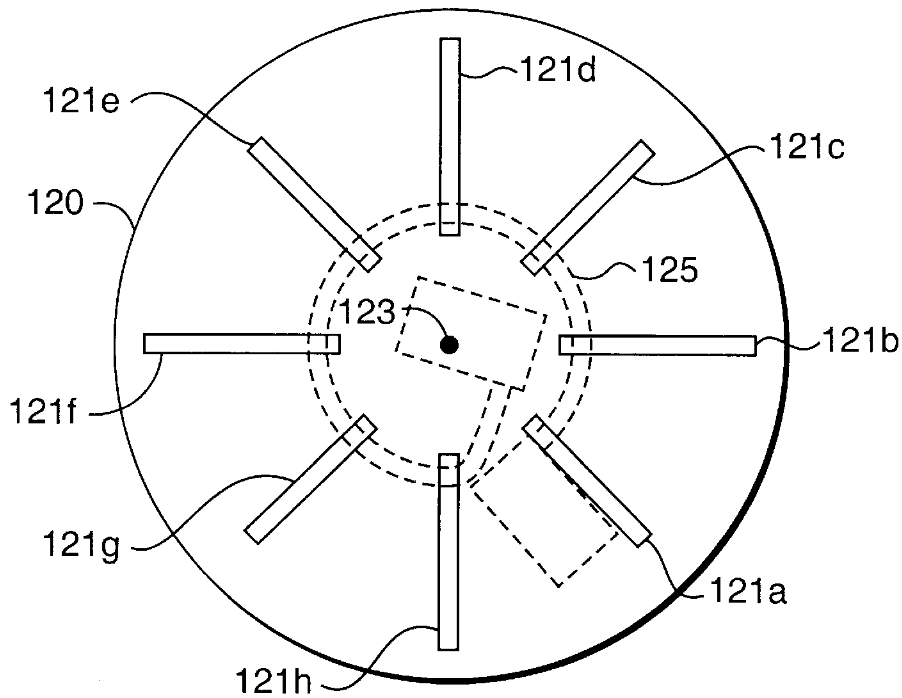
121d
121e
121c
120
125
123
121b
121f
121g
121a
121h

FIG. 11

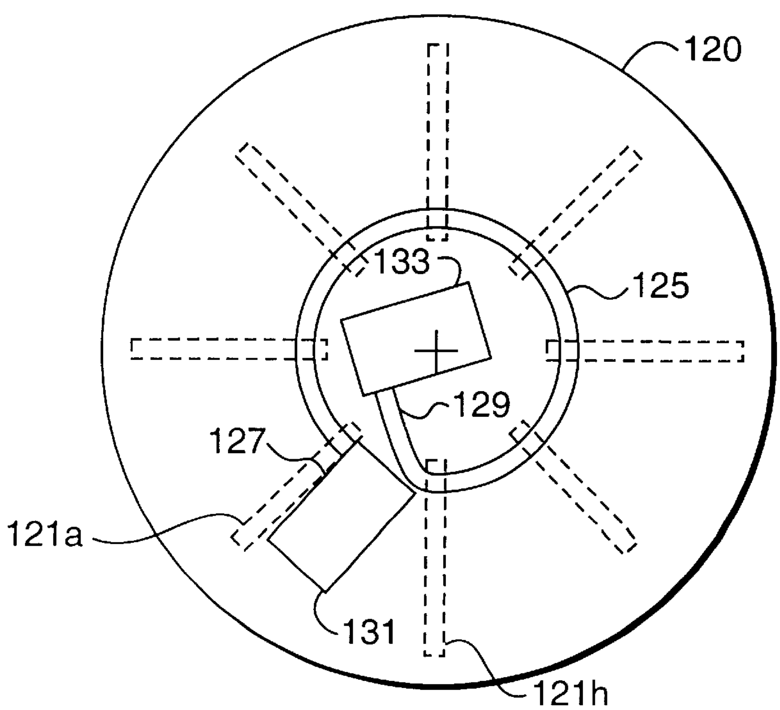
120
133
125
129
127
121a
131
121h

FIG. 12

APERTURE COUPLED SLOT ARRAY ANTENNA

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to planar broadband antennas and, more particularly, to an antenna for transmitting or receiving circularly-polarized signals.

2. Description of the Prior Art

Antennas producing circularly-polarized signals are known in the art. U.S. Pat. No. 5,861,848, issued to Iwasaki, for example, discloses a circularly polarized wave patch antenna with short circuit portion. The directivity of a patch antenna can be increased by incorporation of a choke ring ground plane, but this increases the weight of the antenna.

U.S. Pat. No. 5,815,122, issued to Nurnberger et al., for example, discloses a slot spiral antenna with a single spiral slot on one side of the antenna, and a spiral microstrip feed line on the reverse side. The reference teaches primarily a single-slot configuration which results in an antenna having a low directivity. Moreover, the placement of an additional component, such as a low-noise amplifier, on the antenna itself is impractical.

While the art describes planar antennas producing circularly-polarized radiation, there remains a need for improvements that offer advantages and capabilities not found in presently available devices, and it is a primary object of this invention to provide such improvements. It is another object of the invention to provide such a planar antenna with an improved directivity.

It is yet another object of the present invention to provide a slot array antenna having a distribution feed line which matches the input/output signals with the spatial angular configuration of the antenna slots.

It is further another object of the present invention to provide such a planar antenna which allows for the mounting of active circuitry on the antenna substrate.

Other objects of the invention will be obvious, in part, and, in part, will become apparent when reading the detailed description to follow.

SUMMARY OF THE INVENTION

A planar antenna includes a nonconductive substantially planar substrate and a transmission line disposed on one surface, a segment of the transmission line forming an arc of radius R centered on the antenna axis. A conductive layer on the other antenna surface includes two or more slotted openings, each slotted opening having one end located within a distance R of the antenna axis, such that, when an electromagnetic signal is fed into one end of the transmission line, electromagnetic energy is sequentially coupled into the slotted openings, and a circularly-polarized signal is radiated from the antenna substantially in the direction of the antenna axis. The electrical phase length of the transmission line is matched to the spatial angular difference between two consecutive slotted openings, so as to provide for a phased-array operation.

An amplifier or a connector may be electrically connected to one or both ends of the transmission line, or one end of the transmission line may be terminated in an impedance load to form a leaky-wave antenna. The slotted openings may comprise either or both straight and curved segments, and may be of the same or unequal lengths. Curved slotted openings may be oriented clockwise or counter-clockwise to transmit or receive either left-handed or right-handed polarized signals.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of which:

FIG. **1** is a diagrammatical view of the back side of an antenna in accordance with the present invention showing an arc-shaped transmission line disposed about an antenna axis;

FIG. **2** is a cross-sectional view of the antenna of FIG. **1** showing a conductive plane disposed on the antenna front side;

FIG. **3** is a diagrammatical view of the front side of the antenna of FIG. **1** showing an array of slotted openings disposed in the conductive plane;

FIG. **4** is an end view of the antenna of FIG. **3** showing the placement of an optional reflector to increase the proportion of electromagnetic energy transmitted in the antenna forward direction;

FIG. **5** is a first embodiment of an antenna including four equal-length slotted openings arrayed at 90° intervals about the antenna axis;

FIG. **6** is a view of the back side of the antenna of FIG. **5** showing an signal amplifier and an impedance load attached to the ends of a transmission line;

FIG. **7** is a second embodiment of an antenna including curved slotted openings with straight radial slotted segments to increase coupling between the slotted openings and a transmission line;

FIG. **8** is a third embodiment of an antenna including clockwise spiral slotted openings of two different lengths for transmitting or receiving left-hand polarized signals of two different wavelengths;

FIG. **9** is a view of the back side of the antenna of FIG. **8** showing a wide transmission line for optimally coupling signals of two different wavelengths;

FIG. **10** is a front view of a fourth embodiment of an antenna with high directivity including twelve spiral-shaped slotted openings equally arrayed about the antenna axis;

FIG. **11** is a front view of a fifth embodiment of an antenna including an array of straight slotted openings; and

FIG. **12** is a rear view of the antenna of FIG. **11** showing low-noise signal amplifiers attached to the ends of a transmission line.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

FIG. **1** is a diagrammatical view showing the back side of a substantially planar antenna **10** for receiving or transmitting electromagnetic signals of wavelength λ, in accordance with the present invention. A back surface **13** of the antenna **10** is bounded by a peripheral edge **17**. The peripheral edge **17** encloses an antenna axis **11** oriented orthogonal to the back surface **13**. A transmission line **21**, which may be a microstrip, a coplanar waveguide, or other such conductive component as known in the relevant art, is disposed on the back surface **13**. The transmission line **21** includes an input end **23** for receiving or outputting the electromagnetic signals. The input end is electrically connected by a first conductive lead **12** to a connector **22**, such as an RF connector, for interfacing with external circuitry. A terminal end **25** of the transmission line **21** is electrically connected to a load impedance **24** via a second conductive lead **14**. The transmission line **21** is in the shape of a circular arc, where an inside edge **29** of the transmission line **21** lies at a radius of R and an outside edge **27** lies at a radius of R+w from the antenna axis **11**. The guided wave length of the transmission line is equal to one or more transmitted (or received) wavelengths λ.

FIG. **2** is a cross-sectional view of the antenna **10** as indicated by the sectional arrows in FIG. **1**. The antenna **10** comprises a substrate **19** of nonconductive or dielectric material having a thickness t, where the transmission line **21** is disposed on the back surface **13** of the substrate **19** and a conductive layer **31** is disposed on a front surface **15** of the substrate **19**. The front surface **15** is likewise bounded by the peripheral edge **17**.

FIG. **3** is a diagrammatical view of the front side of the antenna **10** showing that the conductive layer **31** includes a plurality of similar curved, slotted openings **33**, **35**, **37**, and **39**, where each slotted opening **33**, **35**, **37**, and **39** extends through the conductive layer **31** to the front surface **15** of the substrate **19**. The antenna **10** may thus be fabricated from a two-layer printed circuit board (PCB), where the transmission line **21** and the slotted openings **33**, **35**, **37**, and **39** can be formed by suitably etching portions of the respective cladding layers to form the slotted openings **33**, **35**, **37**, and **39** and the transmission line **21**. It should be understood that, although four slotted openings are shown for purpose of illustration, the present invention is not limited to this number and may comprise m slotted openings of varying shapes and lengths, where m≧2, as explained in greater detail below.

Moreover, the slotted openings can be curved in shape as shown, or can be straight segments or a combination of both straight and curved segments, as described in greater detail below. The curved shapes can be a conical section (i.e., a circular, elliptical, parabolic, or hyperbolic arc), an Archimedean spiral, a logarithmic spiral, or an exponential spiral. Straight slotted openings are equivalent to dipoles and, as such, a single slotted opening produces a linearly polarized signal. However, an array of straight slotted openings can be used to transmit, or receive, a circularly-polarized signal, as described in greater detail below. Circular polarization can also be produced by using an array of curved slotted openings, where the respective slotted openings are curved in the direction of the desired circular polarization (i.e., a clockwise curvature to receive or transmit left-hand circularly polarized signals). By using curved slotted openings having the equivalent guided wave lengths of straight slotted openings, the physical size of the antenna can be reduced.

The slotted openings **33**, **35**, **37**, and **39** have respective axial ends **33***a*, **35***a*, **37***a*, and **39***a* proximate the antenna axis **11**, and respective peripheral ends **33***p*, **35***p*, **37***p*, and **39***p* proximate the peripheral edge **17**. Axial ends **33***a*, **35***a*, **37***a*, are, respectively, d_i, d_2, d_3, and d_4 from the antenna axis **11** where d_i<R. That is, the respective axial ends **33***a*, **35***a*, **37***a*, and **39***a* of the respective slotted opening **33**, **35**, **37**, and **39** lie inside the circle of radius R defined by the transmission line **21** (here shown in phantom) on the opposite side of the substrate **19**. Accordingly, when the antenna **10** is used to transmit signals, electromagnetic energy is fed into the transmission line **21** and is electromagnetically coupled to the slotted opening **33**, **35**, **37**, and **39**. This coupling occurs at the four respective regions where the slotted openings **33**, **35**, **37**, and **39** which lie on the front surface **15**, are located most proximate to and directly opposite the transmission line **21** which lies on the back surface **13** of the planar antenna **10**.

For example, a portion of the slotted opening **33** is located a distance equivalent to the substrate thickness t from the transmission line **21** at a coupling region **43**. As is well known in the relevant art, the electromagnetic energy passing through transmission line **21** will produce a radiating field across the slotted opening **33** in the coupling region **43**. This electromagnetic energy will be similarly coupled into slotted openings **35**, **37**, and **39** at coupling regions **45**, **47**, and **49** respectively. The degree of coupling is a function of the thickness t of the substrate **19**, the width w of the transmission line **21**, the width v of the slotted opening **33**, and the dielectric properties of the substrate **19**. Conversely, when the antenna **10** is used to receive signals, radiation energy is received at the slotted openings **33**, **35**, **37**, and **39** is coupled into the transmission line **21** at the respective coupling regions **43**, **45**, **47**, and **49**.

As can be appreciated by one skilled in the relevant art, electromagnetic energy radiated by the antenna **10** is emitted in both directions along the antenna axis **11**. To increase the proportion of energy emitted in the forward direction and reduce the backlobe radiation, a reflector **40** may be emplaced in opposed parallel relationship to the back surface **13** of the antenna **10**, as shown in FIG. **4**. In an alternative embodiment, an enclosed cavity (not shown) could be used in place of the reflector **40** as is well-known in the relevant art. The radiation pattern emitted from the antenna **10**, as well as the radiation pattern roll-off characteristics, can also be varied as desired by increasing or decreasing the separation between the reflector **40** and the antenna **10**.

FIG. **5** is the front view of a first embodiment of a planar antenna **50** in accordance with the present invention. The planar antenna **50** includes four similar spiral-shaped slotted openings **53**, **55**, **57**, and **59** each of width v and guided wave length L_{GW} symmetrically arrayed about an antenna axis **51** at angular intervals of

$$\frac{\pi}{2}$$

radians. This configuration provides for a phased-array slot antenna. Since the slotted openings **53**, **55**, **57**, and **59** curve in the counter-clockwise direction, the transmitted or received signals will be right-hand polarized. Conversely, signals having a left-hand polarization are produced (or received) when the slotted openings **53**, **55**, **57**, and **59** are curved in the clockwise direction. Unwanted cross-polarization is minimized by keeping the opening width v narrow in comparison to the guided wave length L_{GW}. The shape of each of the slotted openings **53**, **55**, **57**, and **59** can be described best in polar coordinates using the antenna axis **51** as origin. The radial distances r(θ) of the interior edges of the slotted openings **53**, **55**, **57**, and **59** increase from r_a at the respective axial ends **53***a*, **55***a*, **57***a*, and **59***a*, to a maximum radius of r_p at the respective peripheral ends **53***p*, **55***p*, **57***p*, and **59***p*. The radial distance from the antenna axis **51** to the inside edge of any of the slotted opening **53**, **55**, **57**, and **59** increases with the polar angle θ and is also a function of the interval spacing Δr for each spiral-shaped slotted opening where $\Delta r \equiv r(\theta+2\pi)-r(\theta)$. For the slotted opening **53**, the radial distance from the antenna axis **51** can be described by means of the equation,

$$r_{53}(\theta, \Delta r) = r_a + \Delta r\frac{\theta}{2\pi}. \quad (1$$

The slotted opening **55** is spatially offset from the slotted opening **53** by

$$\frac{\pi}{2}$$

radians (90°). Similarly, the slotted opening **57** is spatially offset by π radians (180°), and the slotted opening **59** is spatially offset by

$$\frac{3\pi}{2}$$

(270°). The radial distances r(θ, Δr) of the interior edges of the three slotted openings **55**, **57**, and **59** can thus be determined by the respective equations,

$$r_{55}(\theta, \Delta r) = r_a + \Delta r \frac{\theta - \frac{\pi}{2}}{2\pi}, \theta \geq \frac{\pi}{2} \quad (2$$

$$r_{57}(\theta, \Delta r) = r_a + \Delta r \frac{\theta - \pi}{2\pi}, \theta \geq \pi \quad (3$$

$$r_{59}(\theta, \Delta r) = r_a + \Delta r \frac{\theta - \frac{3\pi}{2}}{2\pi}, \theta \geq \frac{3\pi}{2} \quad (4$$

The guided wave length L_{GW} of each of the slotted openings **53**, **55**, **57**, and **59** is specified to be a multiple of quarter-wavelengths of the receiving or transmitting signal in order to maximize the antenna efficiency

$$\left(\text{i.e., } L_{GW} = \frac{n\lambda}{4}\right).$$

In the configuration shown, each spiral-shaped slotted opening subtends an angle of θ_p, where

$$\frac{n\lambda}{4} = \int_0^{\theta p} \left(\frac{\Delta r}{2\pi} \sqrt{1+\theta^2}\right) d\theta \quad (5$$

The width v of each of the slotted openings **53**, **55**, **57**, and **59** is specified to be substantially smaller than the guided wave length and large enough to enable good electromagnetic coupling between the respective slotted opening **53**, **55**, **57**, and **59** and a transmission line **61**, best seen in FIG. **6** which is a rear view of the planar antenna **50**. The transmission line **61** "crosses" each of the slotted openings **53**, **55**, **57**, and **59** at respective coupling regions **63**, **65**, **67**, and **69**. The coupling regions **63**, **65**, **67**, and **69** are offset by

$$\frac{\pi}{2}$$

radians (90°) from one another. This configuration provides for matching the electrical phase differences in the coupling regions **63**, **65**, **67**, and **69** (i.e., differences of 90°) with the spatial differences of the slotted openings **53**, **55**, **57**, and **59** when the guided wave length of the transmission line **61** is tuned to be one wavelength λ. A single, omnidirectional beam is produced when the guided wave length of the transmission line **61** is one wavelength λ, a squinted beam is produced when the guided wave length is less than one wavelength, and multiple directional beams are produced when the guided wave length of the transmission line **61** is more than one wavelength.

A signal is transmitted (or received) by means of a signal source (or receiver) connected to an input/output end **62** of the transmission line **61** via a low-noise amplifier **71**. A connector **75** provides for connecting the transmitted (or received) signal to external circuitry via a coaxial cable, an optical fiber, or a waveguide. An impedance load **73** is coupled to a terminal end **64** of the transmission line **61** to provide a leaky-wave antenna configuration and to thus ensure a uniform amplitude coupling to all slotted openings **53**, **55**, **57**, and **59**. Alternatively, the connector **75** can be directly attached to the input/output end **62** of the transmission line **61** and the amplifier **71** can be located on a separate circuit board.

For the configuration shown, a transmitted signal originating in the low-noise amplifier **71** and terminating in the impedance load **73** passes through the transmission line **61** in a counter-clockwise direction (as viewed from the front of the planar antenna **50**). As the transmitted signal is successively coupled to the slotted openings **53**, **55**, **57**, and **59** at the respective coupling regions **63**, **65**, **67**, and **69**, a right-hand polarized signal is emitted from the planar antenna **50**. Alternatively, the signal can be transmitted through the transmission line **61** in a clockwise direction and the slotted openings **53**, **55**, **57**, and **59** can be curved in a clockwise direction for a transmitted (or received) signal which is left-hand polarized. For a configuration in which the signal travels in the direction opposite to the direction of the spiral slotted openings, both right-hand and left-hand polarized radiation is transmitted (or received).

In a second embodiment, shown in FIG. **7**, an antenna **80** comprises an array of four slotted openings **81**, **83**, **85**, and **89** coupled to the transmission line **61** (on the back side of the antenna **80**). To improve electromagnetic coupling to the transmission line **61**, the slotted openings **81**, **83**, **85**, and **87** each include a straight, radial segment **89** oriented at a right angle to the transmission line **61**. The slotted openings **81**, **83**, **85**, and **87** together with the respective radial segments **89** are tuned so as to optimally transmit (or receive) a specified wavelength λ. Because slotted antennas are broadband, the antenna **80** can transmit (or receive) a spectral band of wavelengths, in addition to radiation of wavelength λ. If the spectral band of wavelengths lies within 30% of λ, a slotted opening tuned to a guided wave length λ can also be used for transmitting (or receiving) the spectral band wavelengths. For wavelengths lying outside this spectral band, a second slotted opening of different guided wave length is used.

For example, in the third embodiment shown in FIG. **8**, an antenna **90** is configured to transmit and receive left-hand polarized signals at two wavelengths, λ_1 and λ_2 Two slotted openings **91** and **95** are tuned for the longer wavelength λ_1, and two slotted openings **93** and **97** are tuned for the shorter wavelength λ_2. The slotted opening **91** can be tuned to the wavelength λ_1, by having a guided wave length L_{GW} of: i) one wavelength (λ_1), ii) two wavelengths ($2\lambda_1$), iii) one-half wavelength

$$\left(\frac{\lambda_1}{2}\right),$$

iii) one-quarter wavelength

$$\left(\frac{\lambda_1}{4}\right),$$

or iv) some other multiple or fraction of a wavelength

$$\left(\frac{a\lambda_1}{b}\right).$$

The antenna **90** comprises a transmission line **101** having a greater width in comparison to the width of transmission line **61** (in FIG. **6**). As best seen in FIG. **9**, the transmission line **101** has an inside edge **103** of radius of curvature R_1 and an outside edge **105** of radius of curvature $R_2=R_1+w$. As well-known in the relevant art, a signal propagating within the transmission line **101** will appear mostly at the edges **103** and **105**. The guided wave length along the inside edge **103** is smaller than the guided wave length along the outside edge **105** by the fraction

$$\frac{R_1}{R_2}.$$

By selecting suitable values for R_1 and R_2, the transmission line **101** can be optimized for coupling more than one wavelength into the array of slotted openings **91**, **93**, **95**, and **97**.

As stated above, the invention is not limited to a single frequency or to only four slotted openings. In a fourth embodiment, shown in FIG. **10**, an antenna **110** comprises six slotted openings **111** tuned to a first wavelength λ_1 and six slotted openings **113** tuned to a second, shorter wavelength λ_2. The array of slotted openings **111** are disposed about an antenna axis **115** within the array of slotted openings **113**. The six slotted openings **111** are spaced apart from one another at angular intervals of

$$\frac{\pi}{3}$$

radians (60°), and the six slotted openings **113** are spaced apart from one another at angular intervals of

$$\frac{\pi}{3}$$

radians (60°). All twelve slotted openings **111** and **113** are coupled to a transmission line (not shown) located on the back side of the antenna **110**. With twelve slotted openings, the antenna **110** has a higher directivity and a greater pattern roll-off from boresight to antenna horizon than, for example, the antenna **50**. in FIG. **5**, comprising four slotted openings.

In a fifth embodiment, shown in FIG. **11**, an antenna **120** comprises eight straight slotted openings **121***a*, **121***b*, . . . , and **121***h* arrayed about an antenna axis **123**. Each slotted opening **121***a*–**121***h* is coupled to a transmission line **125** on the back side of the antenna **120**, as shown in FIG. **12**. A first end **127** of the transmission line **125** is connected to a first signal amplifier **131**, and a second end **129** of the transmission line **125** is connected to a second signal amplifier **133**. There is also provided a switching circuit (not shown) which enables either the first signal amplifier **131** or the second signal amplifier **133** to transmit a corresponding signal through the transmission line **125**. A signal transmitted by the first signal amplifier **131** travels in a counter-clockwise direction, from the first end **127** to the second end **129**. The input impedance of the second signal amplifier **133** provides an impedance load to the signal transmitted by the first signal amplifier **131**. The counter-clockwise signal is coupled first into the straight slotted opening **121***a* and last into the straight slotted opening **121***h*. This coupling sequence produces an emitted signal having left-handed circular polarization.

Similarly, a signal transmitted by the second signal amplifier **133** travels in a clockwise direction, from the second end **129** to the first end **127**. The input impedance of the first signal amplifier **131** provides an impedance load to the signal transmitted by the second signal amplifier **133**. The clockwise signal is coupled first into the straight slotted opening **121***h* and last into the straight slotted opening **121***a*. This coupling sequence produces an emitted signal having right-handed circular polarization. In this way, a single antenna can be used to transmit signals of either polarization. Alternatively, the second signal amplifier **133** can be replaced by a receiver (not shown), and the antenna **120** can be used to transmit left-handed circularly polarized signals via first signal amplifier **121** and to receive right-handed circularly polarized signals via the receiver. If the first signal amplifier is also replaced by a second receiver (not shown), both left-hand polarized and right-hand polarized signals can be received by the antenna **120**.

While the invention has been described with reference to particular embodiments, it will be understood that the present invention is by no means limited to the particular constructions and methods herein disclosed and/or shown in the drawings, but also comprises any modifications or equivalents within the scope of the claims.

What is claimed is:

1. An antenna **(10)**, suitable for transmitting and receiving electromagnetic signals of wavelength λ, said antenna comprising:

a nonconductive substantially planar substrate **(19)** having first **(13)** and second **(15)** surfaces bounded by a common peripheral edge **(17)**, said peripheral edge enclosing an antenna axis **(11)** orthogonal to said first and second surfaces;

a transmission line **(21)** disposed on said first surface, said transmission line comprising a first end **(23)**, a second end **(25)**, and an inner edge **(29)** extending between said first and second ends, at least a portion of said inner edge forming an arc of:radius R centered on said antenna axis; and

a conductive layer **(31)** disposed on said second surface, said conductive layer comprising a plurality of m slotted openings **(33)**, each said slotted opening having one end located within a distance R of said antenna axis and having an essentially uniform width that is substantially less than the length,

whereby, when an electromagnetic signal is fed into said first end, electromagnetic energy is coupled sequentially into respective said slotted openings such that a radiated signal is transmitted from said slotted openings substantially in the direction of said antenna axis.

2. The antenna of claim **1** wherein said transmission line inner edge has a guided wave length of at least λ.

3. The antenna of claim **1** wherein said transmission line comprises at least one member of the group consisting of a microstrip and a coplanar waveguide.

4. The antenna of claim **1** further comprising a connector electrically attached to one said transmission line end.

5. The antenna of claim **1** further comprising at least one amplifier electrically connected to at least one said transmission line end.

6. The antenna of claim **1** further comprising an impedance load electrically connected to one said transmission line end.

7. The antenna of claim **1** wherein at least a first said slotted opening has a guided wave length of

$$\frac{a\lambda}{b}.$$

8. The antenna of claim **7** wherein a second said slotted opening has a guided wave length greater than the guided wave length of said first slotted opening.

9. The antenna of claim **1** wherein said m slotted openings are arrayed about said antenna axis such that at least two adjacent said slotted openings are spatially separated by an angle of

$$\frac{2\pi}{m}.$$

10. The antenna of claim **1** wherein at least one said slotted opening comprises a straight slotted portion.

11. The antenna of claim **1** wherein at least one said slotted opening comprises a curved slotted portion.

12. The antenna of claim **11** wherein said curved slotted portion comprises a shape selected from the group consisting of a conical-section arc, a spiral arc, a logarithmic arc, and an exponential arc.

13. The antenna of claim **1** further comprising a reflector disposed in spaced parallel relationship to said first surface.

14. The antenna of claim **1** further comprising an enclosed cavity disposed adjacent said first surface.

15. The antenna of claim **1** wherein a given said slotted opening is sized to couple more strongly to electromagnetic energy directed across the slot than to electromagnetic energy directed along the slot.

16. An antenna, suitable for transmitting and receiving electromagnetic signals of wavelengths λ_1 and λ_2, said antenna comprising:

a nonconductive substantially planar substrate having first and second surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said surfaces;

a transmission line disposed on said first surface, said transmission line comprising a first end, a second end, and an inner edge extending between said first and second ends, at least a portion of said inner edge forming an arc of radius R centered on said antenna axis; and

a conductive layer disposed on said second surface,

said conductive layer comprising a first array of m slotted openings, each said first array slotted opening having a peripheral end located proximate said peripheral edge and an axial end located within a distance R of said antenna axis, each said first array slotted opening having a guided wave length of integer multiples

$$\frac{\lambda_1}{4},$$

between said peripheral end and said axial end, at least one said first array slotted opening spatially separated from an adjacent said first array slotted opening by an angle of

$$\frac{2\pi}{m};$$

said conductive layer further comprising a second array of m slotted openings, each said second array slotted opening having a peripheral end located proximate said peripheral edge and an axial end located within a distance R of said antenna axis, each said second array slotted opening having a guided wave length of integer multiples of

$$\frac{\lambda_2}{4}$$

between said peripheral end and said axial end, at least one said second array slotted opening spatially separated from an adjacent said second array slotted opening by an angle of

$$\frac{2\pi}{m}$$

whereby, when an electromagnetic signal is fed into said transmission line via said first end, electromagnetic energy is sequentially coupled into respective said slotted openings such that a radiated signal having a wavelength of either or both λ_1 and λ_2 is transmitted from said slotted openings substantially in the direction of said antenna axis.

17. The antenna of claim **16** wherein at least one said slotted opening comprises a shape selected from the group consisting of a conical-section arc, a spiral arc, a logarithmic arc, and an exponential arc.

18. The antenna of claim **16** further comprising a connector electrically attached to said transmission line first end.

19. The antenna of claim **16** further comprising at least one amplifier electrically connected to at least one of said first and second transmission line ends.

20. The antenna of claim **16** further comprising an impedance load electrically connected to said transmission line second end.

21. The antenna of claim **16** further comprising a reflector disposed in spaced parallel relationship to said substrate first surface.

22. The antenna of claim **16** further comprising an enclosed cavity disposed adjacent said substrate first surface.

23. A planar antenna suitable for transmitting or receiving an electromagnetic signal, said antenna comprising:

an array of m slotted openings disposed in a top surface of the planar antenna, said slotted openings for receiving or transmitting the electromagnetic signal, said array of slotted openings defining an antenna axis; and

a transmission line for sequentially coupling the received or transmitted electromagnetic signal with said slotted openings, said transmission line disposed on a bottom surface of the antenna so as to substantially enclose said antenna axis, said transmission line comprising a plurality of m coupling regions, each said coupling region comprising a segment of said transmission line disposed proximate a corresponding said slotted opening such that an electromagnetic signal transmitted through said transmission line is coupled sequentially into respective said slotted openings surface of the antenna so as to substantially enclose said antenna axis.

24. The antenna of claim 23 wherein at least one said slotted opening comprises a curved slotted portion.

25. The antenna of claim 23 wherein said slotted openings each have a width that is sub-stantially narrower than the length of the slot.

26. The antenna of claim 25 wherein a given said slotted opening is sized to couple more strongly to electromagnetic energy directed across the slot than to electromagnetic energy directed along the slot.

27. A method for emitting a circularly-polarized signal from a planar antenna, said method comprising the steps of:

transmitting a first electromagnetic signal of wavelength λ_1 along a transmission line disposed on a bottom antenna surface, said transmission line comprising an arc-shaped segment having a radius R centered on an antenna axis; and

sequentially coupling said transmitted signal into two or more slotted openings formed within a conductive layer disposed on a top antenna surface, each said slotted opening having an end located within a distance R of the antenna axis, said slotted openings arrayed about the antenna axis such that a signal is emitted having wavelength λ_1 with one of a right-hand or a left-hand circular polarization.

28. The method of claim 27 wherein said step of sequentially coupling comprises the step of producing a radiation field extending from said transmission line to said slotted openings.

29. The method of claim 27 further comprising the steps of:

transmitting a second electromagnetic signal of wavelength λ_2 along said transmission line; and

sequentially coupling the transmitted signal into said slotted openings such that a signal of wavelength λ_2 is emitted.

30. The method of claim 27 further comprising the steps of:

transmitting a second electromagnetic signal of wavelength λ_2 along said transmission line in a direction opposite to that of the direction of transmission of said first electromagnetic signal; and

reverse sequentially coupling the transmitted signal into said slotted openings such that a signal is emitted having the other of a right-hand or a left-hand circular polarization.

31. A method for receiving a circularly-polarized radiated signal by means of a planar antenna, said method comprising the steps of:

receiving the radiated signal at two or more slotted openings formed within a conductive layer disposed on a top surface of the antenna, each said slotted opening having a first end located proximate an antenna periphery and a second end located within a distance R of the antenna axis; and

sequentially coupling the received signal from each said slotted opening into a transmission line disposed on a bottom surface of the antenna, said transmission line comprising an arc-shaped segment having an edge radius of R centered on the antenna axis.

32. An antenna (10), suitable for transmitting and receiving electromagnetic signals of wavelength λ, the antenna comprising:

a nonconductive substantially planar substrate (19) having first (13) and second (15) surfaces bounded by a common peripheral edge (17), the peripheral edge enclosing an antenna axis (11) orthogonal to the first and second surfaces;

a transmission line (21) disposed on the first surface, the transmission line comprising a first end (23), a second end (25), and an inner edge (29) extending between the first and second ends, at least a portion of the inner edge forming an arc of radius R centered on the antenna axis, the transmission line being terminated at the second end by electrical connection to a load impedance (24); and

a conductive layer (31) disposed on the second surface, the conductive layer comprising a plurality of m slotted openings (33), each the slotted opening having one end located within a distance R of the antenna axis and having a width that is substantially less than the length,

whereby, when an electromagnetic signal is fed into the first end of the transmission line, electromagnetic energy is coupled sequentially into the respective slotted openings such that a radiated signal is transmitted from the slotted openings substantially in the direction of the antenna axis.

33. An antenna (10), suitable for transmitting and receiving electromagnetic signals of wavelength λ, the antenna comprising:

a nonconductive substantially planar substrate (19) having first (13) and second (15) surfaces bounded by a common peripheral edge (17), the peripheral edge enclosing an antenna axis (11) orthogonal to the first and second surfaces;

a transmission line (21) disposed on the first surface, the transmission line comprising a first end (23), a second end (25), and an inner edge (29) extending between the first and second ends, at least a portion of the inner edge forming an arc of radius R centered on the antenna axis; and

a conductive layer (31) disposed on the second surface, the conductive layer comprising a plurality of m slotted openings (33), each the slotted opening having one end located within a distance R of the antenna axis, a width that is substantially less than the length, and an electrical length of integer multiples of

$$\frac{\lambda}{4},$$

with at least one slotted opening spatially separated from an adjacent slotted opening by an angle of

$$\frac{2\pi}{m},$$

whereby, when an electromagnetic signal is fed into the first end of the transmission line, electromagnetic energy is coupled sequentially into the respective slotted openings such that a radiated signal is transmitted from the slotted openings substantially in the direction of the antenna axis.

34. The antenna of claim 33 further including a reflector disposed in spaced parallel relationship to the first surface of the substrate.

35. The antenna of claim 33 further including an enclosed cavity disposed adjacent the first surface of the substrate.

36. The antenna of claim **33** wherein said transmission line inner edge has a guided wave length of at least λ.

37. The antenna of claim **33** wherein the transmission line comprises at least one member of the group consisting of a microstrip and a coplanar waveguide.

38. The antenna of claim **33** wherein a second of the slotted openings has an electrical length greater than the electrical length of a first of the slotted openings.

39. The antenna of claim **33** wherein at least one of the slotted openings includes a straight portion.

40. The antenna of claim **33** wherein at least one of the slotted openings includes a curved portion.

41. The antenna of claim **40** wherein the curved portion comprises a shape selected from the group consisting of a conical-section arc, a spiral arc, a logarithmic arc, and an exponential arc.

42. The antenna of claim **33** wherein the second end of the transmission line electrically connects to an impedance load.

* * * * *

US006452560B2

(12) **United States Patent**
Kunysz

(10) **Patent No.: US 6,452,560 B2**
(45) **Date of Patent: Sep. 17, 2002**

(54) **SLOT ARRAY ANTENNA WITH REDUCED EDGE DIFFRACTION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/732,849**

(22) Filed: **Dec. 8, 2000**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/375,319, filed on Aug. 16, 1999.

(51) **Int. Cl.**[7] **H01Q 13/10**
(52) **U.S. Cl.** **343/770**; 343/769
(58) **Field of Search** .... 343/700 MS, 767, 343/768, 769, 770, 895, 909; H01Q 1/38, 9/36, 13/10, 9/38

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,568,206 A * 3/1971 Sisson 343/750
3,665,480 A * 5/1972 Fassett 343/754
3,696,433 A * 10/1972 Killion et al. 343/770
4,150,383 A * 4/1979 Andersson et al. 343/771
4,204,212 A 5/1980 Sindoris et al.
4,315,266 A 2/1982 Ellis, Jr.
4,477,814 A 10/1984 Brumbaugh et al.
4,525,720 A 6/1985 Corzine et al.
4,608,572 A * 8/1986 Blakney et al. 343/792.5
4,658,262 A 4/1987 DuHamel
5,220,340 A 6/1993 Shafai
5,313,216 A 5/1994 Wang et al.
5,402,136 A * 3/1995 Goto et al. 343/729
5,451,973 A 9/1995 Walter et al.
5,614,863 A 3/1997 Pierro et al.
5,621,422 A 4/1997 Wang
5,646,633 A 7/1997 Dahlberg
5,712,647 A 1/1998 Shively
5,815,122 A 9/1998 Nurnberger et al.
5,861,848 A 1/1999 Iwasaki
5,929,825 A 7/1999 Niu et al.
5,936,594 A 8/1999 Yu et al.

OTHER PUBLICATIONS

Nurenberger M W et al.: "A New Planar Feed For Slot Spiral Antennas" IEEE Transactions on Antennas and Propagation, US, IEEE Inc. New York, vol. 44, No. 1, 1996, pp. 130–131 XP000549415.

* cited by examiner

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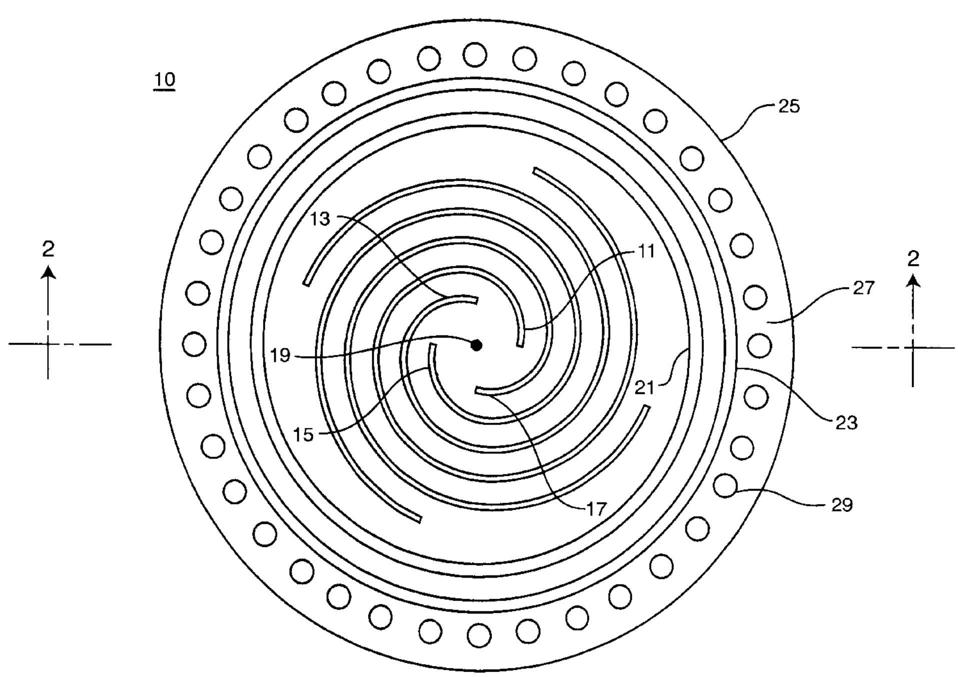
(74) *Attorney, Agent, or Firm*—Cesari and McKenna, LLP

(57) **ABSTRACT**

A slot-array antenna includes a nonconductive substantially planar substrate and a transmission line disposed on a rear substrate surface where one end of the transmission line is connected to an amplifier, a connector, or an impedance load. A conductive layer on the front substrate surface includes a plurality of slotted openings arrayed about an antenna axis. A surface-wave suppression region encloses the array of slotted openings and a plurality of peripheral openings are disposed between the surface-wave suppression region and the peripheral edge of the antenna.

25 Claims, 4 Drawing Sheets



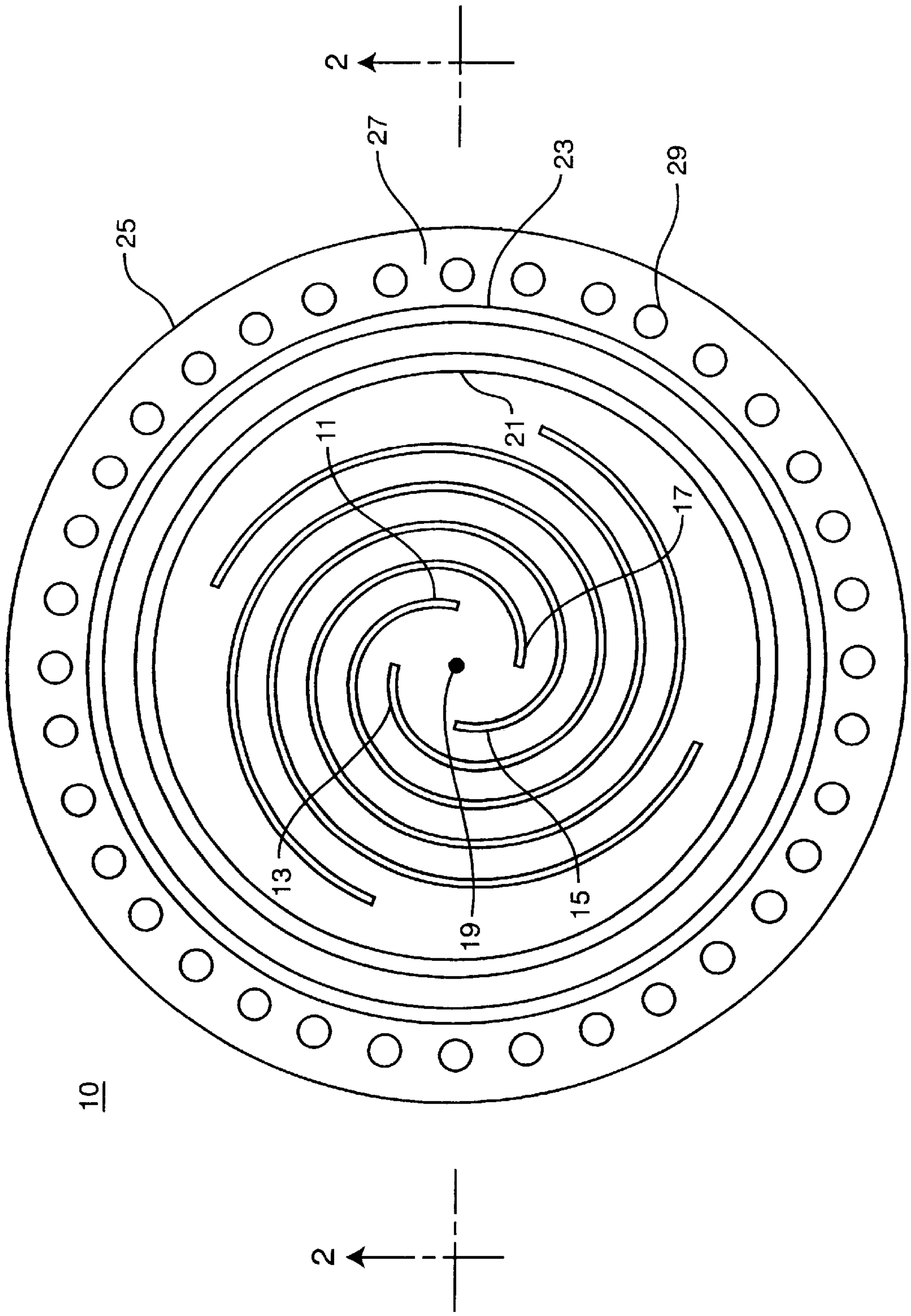


Fig. 1

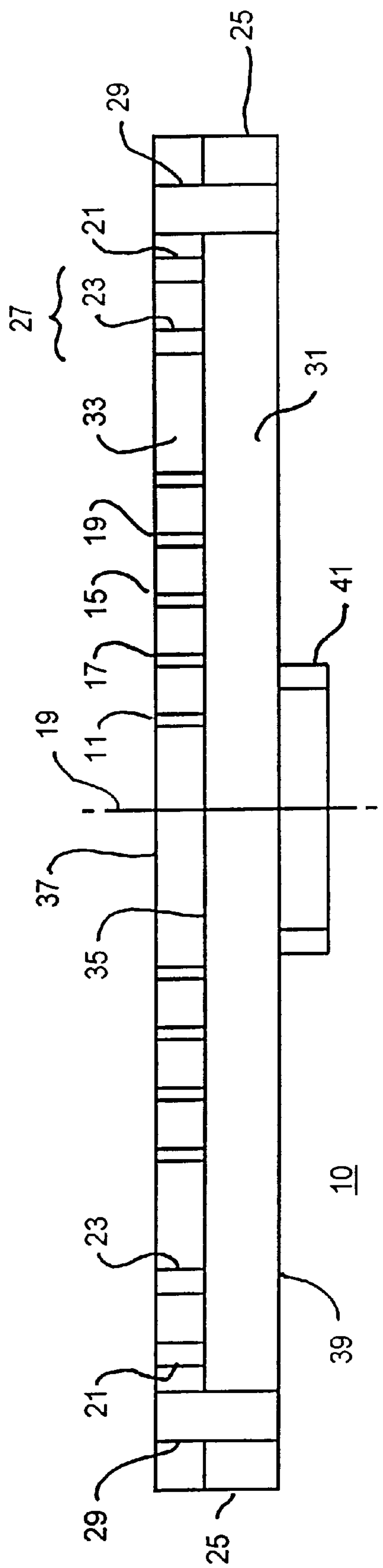


Fig. 2

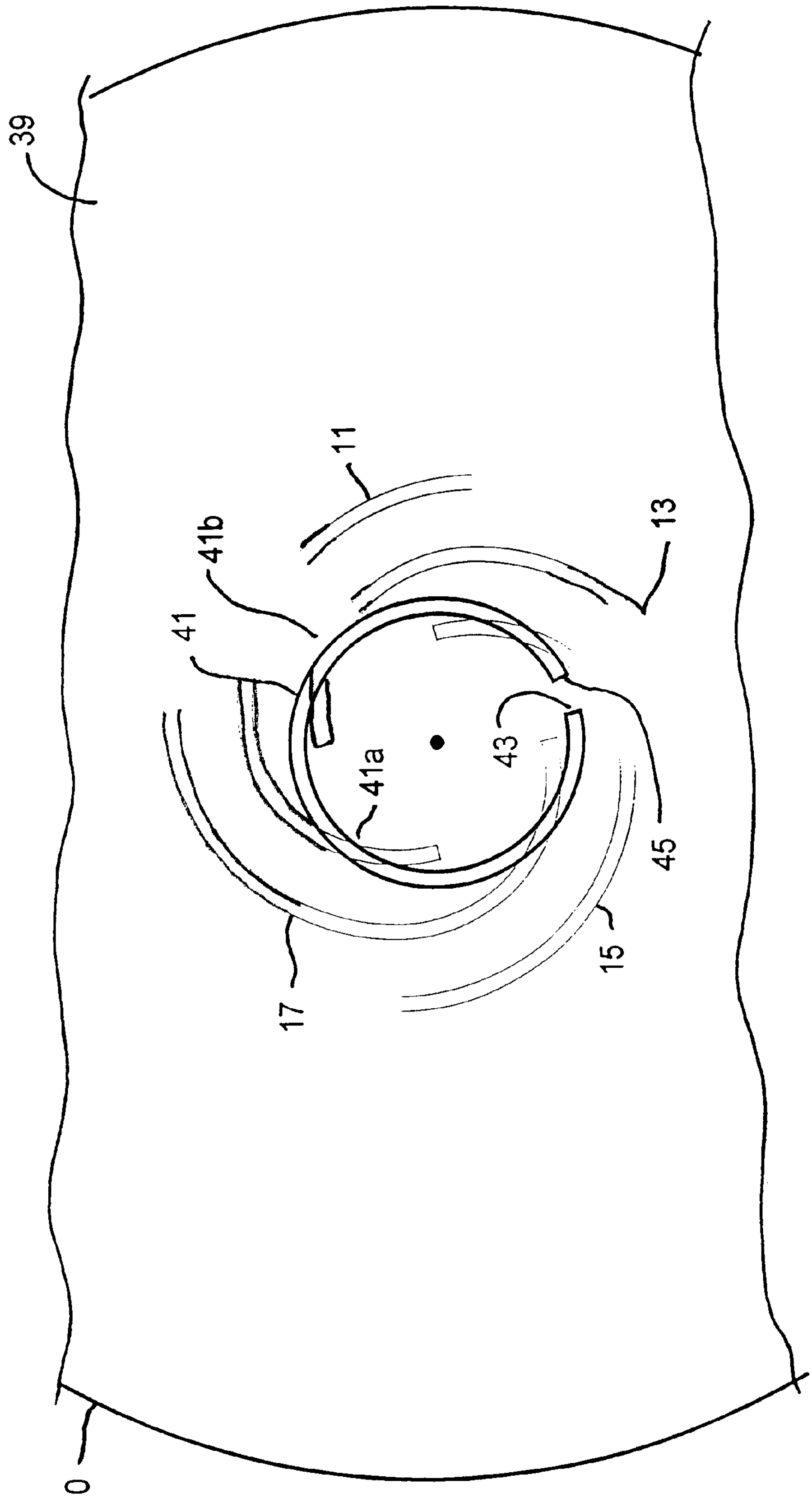


Fig. 3

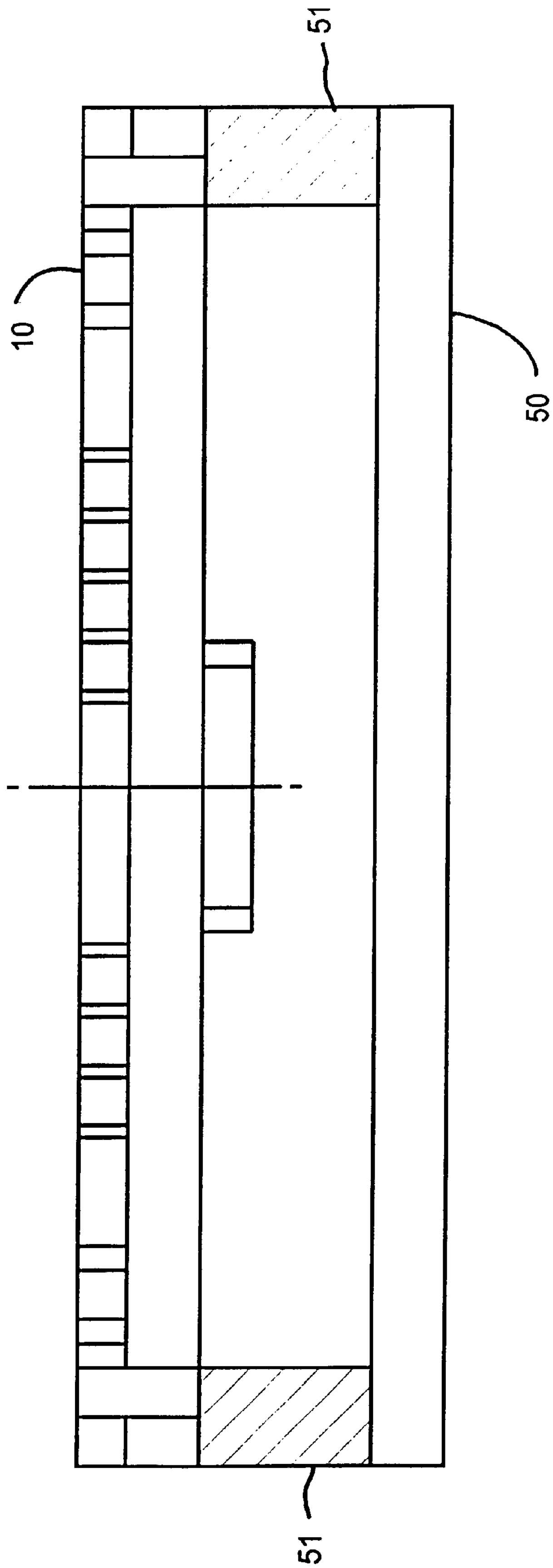


Fig. 4

SLOT ARRAY ANTENNA WITH REDUCED EDGE DIFFRACTION

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a continuation-in-part of commonly-assigned copending U.S. patent application Ser. No. 09/375,319, which was filed on Aug. 16, 1999, by W. Kunysz for an Aperture Coupled Slot Array Antenna.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to planar broadband antennas and, more particularly, to an antenna with reduced edge diffraction.

2. Background Information

Antennas, such as used in Global Positioning Systems (GPS), have differing requirements depending upon the particular application for the antenna. For application to surveying activity, for example, the ideal antenna will receive only those signals originating above the horizontal plane of the antenna, and reject all other signals. Additionally, the ideal antenna will have a known and stable phase center located at the geometric center of the antenna, and have perfect circular polarization characteristics to maximize the reception of incoming right-hand polarized signals. A close approximation to such an ideal antenna can be provided by a patch antenna mounted on a choke ring ground plane. However, such a configuration is large and bulky, prohibiting its use in portable applications such as surveying.

Furthermore, many antenna radiation structures exhibit performance degradation as a result of surface wave excitation at the front surface of the antenna which produces diffractive radiation at the antenna edge. It is thus an object of the present invention to provide a slot array antenna antenna with reduced edge diffraction.

Other objects of the invention will be obvious, in part, and, in part, will become apparent when reading the detailed description to follow.

SUMMARY OF THE INVENTION

A slot-array antenna includes a nonconductive substantially planar substrate, a transmission line disposed on a rear substrate surface, and a conductive layer on the front antenna surface, the conductive layer having an array of slotted openings therein. When an electromagnetic signal is fed into one end of the transmission line and sequentially coupled into the slotted openings, a corresponding signal is emitted from the antenna substantially in the direction of the antenna axis. The front antenna surface also includes a surface wave suppression region enclosing the slotted array and a plurality of through holes disposed between the wave suppression region and the peripheral edge of the antenna to reduce diffraction of the emitted signal at the peripheral edge.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of which:

FIG. **1** is a diagrammatical view of the front surface of a slot array antenna in accordance with the present invention;

FIG. **2** is a cross sectional view of the antenna of FIG. **1**;

FIG. **3** is a diagrammatical view of a transmission line located on the rear surface of the antenna of FIG. **1**, and;

FIG. **4** is an alternative embodiment of the antenna of FIG. **1** which includes a reflector and RF absorbing material.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

FIG. **1** is a diagrammatical view showing the front side of a substantially planar slot-array antenna **10** for receiving or transmitting electromagnetic signals of wavelength λ, in accordance with the present invention. The antenna **10** includes a plurality of curved, slotted openings **11**, **13**, **15**, and **17** which may be of equal lengths, as shown, or of different lengths as a particular application may require. The slotted openings **11**, **13**, **15**, and **17** are arrayed about an antenna axis **19**, or phase center. In the example provided, a first, substantially circular surface wave suppression feature **21** encloses the array of slotted openings **11**, **13**, **15**, and **17**, and a second substantially circular wave suppression feature **23** encloses the first wave suppression feature **21**. The wave suppression features **21** and **23** define a surface-wave suppression region **27**. A plurality of peripheral openings **29**, or through holes, are distributed around the surface-wave suppression region **27** and inside a peripheral edge **25** of the antenna **10** as shown.

It should be understood that a relatively small number of slotted openings, wave suppression features, and peripheral openings are shown in Fig. limited for clarity of illustration, and that the disclosed invention is not restricted to the particular configuration shown. A preferred embodiment, for example, includes an array of twelve equal-length slotted openings, a series of eleven concentric wave suppression features in the surface-wave suppression region, and a distribution of one hundred twelve peripheral openings, all disposed within a diameter of approximately 6.25 inches. The quantity and spacing of the concentric wave suppression features are such that there are three or more, and preferably ten, such features within a radial dimension of approximately one wavelength λ.

FIG. **2** is a diagrammatical cross-sectional view of the antenna **10** as indicated by the sectional arrows in FIG. **1**. The antenna **10** comprises a substrate **31** of a dielectric, or other nonconductive material, and a conductive layer **33** disposed on a front surface **35** of the substrate **31**, where the front surface **35** is bounded by the peripheral edge **25**. As can be seen in cross-section, each slotted opening **11**, **13**, **15**, and **17** extends from a front surface **37** of the conductive layer **33**, through the conductive layer **33**, to the front surface **35** of the substrate.

The surface-wave suppression region **27** comprises a photonic-bandgap (PBG) material disposed in the conductive layer **33**. As is known in the relevant art, a PBG material is a class of periodic dielectrics, where the periodicity may be one-, two-, or three-dimensional. For example, the surface-wave suppression region **27** may include a special texture (not shown) etched in the conductive layer **33** to provide a high impedance for radiation of wavelength λ. A relevant discussion of PBG material may be found in the cited reference by D. Sievenpiper et al. entitled "High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band."

In a preferred embodiment, a three-dimensional PBG material, or photonic crystal (PC) is used for the surface-wave suppression region **27**. As seen in the sectional view, the wave suppression features **21** and **23** are configured as adjacent concentric grooves enclosing the slotted openings **11**, **13**, **15**, and **17**. Thus, the PBG material is formed by this series of concentric grooves disposed between the slotted openings **11**, **13**, **15**, and **17** and the peripheral edge **25**. Each groove extends between the front surface **37** and the front surface **35**. The surface-wave suppression region **27** functions to attenuate or suppress surface waves propagating along the front surface **37** from the slotted openings **11**, **13**, **15**, and **17** toward the peripheral edge **25**. Preferably, the spacing between adjacent wave suppression features is on the order of $\lambda/10$. That is, the spacing interval is substantially less than one wavelength λ.

The peripheral openings **29** extend from the front surface **37** of the conductive layer **33**, through the conductive layer **33** and the substrate **31**, to a back surface **39** of the substrate **31**. The peripheral openings **29** function to suppress surface waves propagating within the substrate **31** by providing a physical diffracting geometry. In a preferred embodiment, the peripheral openings **29** are metallized through-holes approximately 70 mils in diameter and spaced at intervals of approximately 150 mils.

A transmission line **41** is disposed on the back surface **39** of the substrate **31**. As best shown in FIG. **3**, which is a diagrammatical plan view of the back surface **39**, the transmission line **41** is substantially circular with an input end **43**, for receiving or outputting electromagnetic signals, and a terminal end **45** which may be electrically connected to a load impedance (not shown). The transmission line **41** is positioned on the back surface **39** so as to enclose the ends of the slotted openings **11**, **13**, **15**, and **17** (here shown in phantom) and provide for coupling of electromagnetic energy between the transmission line **41** and the slotted openings **11**, **13**, **15**, and **17**. For example, the transmission line **41** overlaps the slotted opening **11** at region **41***a*, and overlaps the slotted opening **13** at region **41***b*. Accordingly, electromagnetic coupling between the transmission line **41** and the slotted opening **11** occurs primarily at the region **41***a*, and electromagnetic coupling between the transmission line **41** and the slotted opening **13** occurs primarily at the region **41***b*.

The transmission line **41** may comprise a microstrip, a coplanar waveguide, or other such conductive component as known in the relevant art. Preferably, the guided-wave length of the transmission line is substantially equal to one or more transmitted (or received) wavelengths λ. A transmission line having a guided wavelength of one λ will produce a single omnidirectional beam emitted in the direction of the antenna axis **19** (i.e., normal to the plane of the antenna **10**). Alternatively, a transmission line having a guided wavelength of nλ will produce n beams equally spaced in the azimuth plane and whose primary angle in the vertical plane will depend on is the phase of excitation of the slotted openings **11**, **13**, **15**, and **17**.

The antenna **10** may thus be fabricated from a two-layer, or double-clad, printed circuit board (PCB), where the transmission line **41** and the slotted openings **11**, **13**, **15**, and **17** can be formed by suitably etching portions of the respective cladding layers. As noted above, the preferred embodiment includes an array of twelve slotted openings spaced at intervals of 30°. However, in alternative embodiments, the slotted openings can be configured in varying shapes and lengths. For example, the slotted openings can be curved in shape as shown, straight segments, or a combination of both straight and curved segments. These alternative configurations are disclosed in commonly-assigned U.S. Pat. No. XXX, incorporated herein in its entirety by reference.

In an alternative embodiment, shown in FIG. **4**, a reflector **50** is included adjacent to the antenna **10** and RF absorbing material **51** is emplaced in the region between the antenna **10** and the reflector **50**. As can be appreciated by one skilled in the relevant art, use of the reflector **50** redirects in the forward direction the rearward radiation emitted by the antenna **10** to improve the antenna gain and reduce the back-lobe radiation.

While the invention has been described with reference to particular embodiments, it will be understood that the present invention is by no means limited to the particular constructions and methods herein disclosed and/or shown in the drawings, but also comprises any modifications or equivalents within the scope of the claims.

What is claimed is:

1. An antenna, suitable for transmitting and receiving electromagnetic signals of wavelength λ, said antenna comprising:

a nonconductive substantially planar substrate having front and rear surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said front surface;

a transmission line disposed on said rear surface;

a conductive layer disposed on said front surface, said conductive layer including

i. a plurality of slotted openings arrayed about said antenna axis, and

ii. a surface-wave suppression region enclosing said array of slotted openings and attenuating surface waves propagating along said front surface from said slotted openings toward said peripheral edge; and

a plurality of peripheral openings disposed between said surface-wave suppression region and said peripheral edge, said peripheral openings extending through said conductive layer and said substrate and attenuating surface waves propagating within said substrate by diffraction;

such that an electromagnetic signal fed into said transmission line is coupled sequentially into respective said slotted openings and transmitted from said slotted openings substantially in the direction of said antenna axis.

2. The antenna of claim **1** wherein said transmission line has a guided-wave length of at least λ.

3. The antenna of claim **1** wherein said transmission line is circular in shape so as to substantially enclose said antenna axis.

4. The antenna of claim **1** wherein said transmission line comprises a plurality of coupling regions, each said coupling region corresponding to one of said slotted openings.

5. The antenna of claim **1** wherein said surface-wave suppression region comprises a member of the group consisting of: photonic bandgap material and photonic crystal.

6. The antenna of claim **1** wherein said surface-wave suppression region comprises a plurality of concentric grooves.

7. The antenna of claim **6** wherein said concentric grooves are spaced at approximate intervals of

$$\frac{\lambda}{10}.$$

8. The antenna of claim **1** wherein said antenna has an approximate diameter of 6.25 inches.

9. The antenna of claim **1** further comprising a reflector disposed adjacent said antenna and RF material disposed between said reflector and said antenna.

10. The antenna of claim **1** further comprising a reflector disposed adjacent said antenna and RF material disposed between said reflector and said antenna.

11. A method of transmitting an electromagnetic signal of wavelength λ, said method comprising the steps of:

providing a nonconductive substantially planar substrate having front and rear surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said front surface;

inputting the electromagnetic signal into a transmission line disposed on said rear surface;

coupling the electromagnetic signal into a plurality of slotted openings arrayed about said antenna axis, said slotted openings formed in a conductive layer disposed on said front surface;

attenuating surface waves propagating along said conductive layer by means of a surface-wave suppression region enclosing said slotted openings; and

attenuating surface waves propagating through said substrate by means of a plurality of peripheral openings disposed between said surface-wave suppression region and said peripheral edge, said peripheral openings extending through said conductive layer and said substrate.

12. The method of claim **11** wherein said transmission line comprises a plurality of coupling regions, each said coupling region corresponding to one of said slotted openings.

13. The method of claim **11** wherein said surface-wave suppression region comprises a member of the group consisting of: photonic bandgap material and photonic crystal.

14. The method of claim **11** wherein said surface-wave suppression region comprises a plurality of concentric grooves.

15. An antenna, suitable for transmitting and receiving electromagnetic signals of wavelength λ, said antenna comprising:

a nonconductive substantially planar substrate having front and rear surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said front surface;

a transmission line disposed on said rear surface, said transmission line having a guided-wave length of at least λ;

a conductive layer disposed on said front surface, said conductive layer including

i. a plurality of slotted openings arrayed about said antenna axis, and

ii. a surface-wave suppression region enclosing said array of slotted openings; and

a plurality of closely spaced peripheral openings;

disposed between said surface-wave suppression region and said peripheral edge, said peripheral openings extending through said conductive layer and said substrate;

such that an electromagnetic signal fed into said transmission line is coupled sequentially into respectived said slotted openings and transmitted from said slotted openings substantially in the direction of said antenna axis and surface waves propagation along said front surfaces from said slotted openings toward said peripheral edge are attenuated by said surface surface-wave suppression region and surface waves propagating within said substrate are attenuated by diffraction by said peripheral openings.

16. The antenna of claim **15** wherein said transmission line comprises twelve coupling regions, each said coupling region corresponding to one of said slotted openings.

17. The antenna of claim **15** wherein said surface-wave suppression region comprises a member of the group consisting of: photonic bandgap material and photonic crystal.

18. The antenna of claim **15** wherein said surface-wave suppression region comprises at least ten concentric grooves.

19. The antenna of claim **18** wherein said concentric grooves are spaced at approximate intervals of

$$\frac{\lambda}{10}.$$

20. The antenna of claim **15** wherein said antenna has an approximate diameter of 6.25 inches.

21. An antenna, suitable for transmitting and receiving electromagnetic signal of wavelength λ, said antenna comprising:

a nonconductive substantially planar substrate having front and rear a surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said front surface;

a transmission line disposed on said rear surface;

a conductive layer disposed on said front surface, said conductive layer including

i. a plurality of slotted openings arrayed about said antenna axis such that an electromagnetic signal fed into said transmission line is coupled sequentially into respective said slotted openings and transmitted from said slotted openings substantially in the direction of said antenna axis, and

ii. a surface-wave suppression region enclosing said array of slotted openings and attenuating surface waves propagating along said front surface from said slotted openings toward said peripheral edge.

22. The antenna of claim **21** wherein said surface-wave suppression region comprises a member of the group consisting of: photonic bandgap material and photonic crystal.

23. The antenna of claim **21** wherein said surface-wave suppression region comprises a plurality of concentric grooves.

24. The antenna of claim **21** wherein said concentric grooves are spaced at approximate intervals of no more than

$$\frac{\lambda}{10}.$$

25. An antenna, suitable for transmitting and receiving electromagnetic signals of wavelength λ, said antenna comprising:

a nonconductive substantially planar substrate having front and rear surfaces bounded by a common peripheral edge, said peripheral edge enclosing an antenna axis orthogonal to said front surface;

a transmission line disposed on said rear surface;

a conductive layer disposed on said front surface, said conductive layer including a plurality of slotted openings arrayed about said antenna axis such that an electromagnetic signal fed into said transmission line is coupled sequentially into respective said slotted openings and transmitted from said slotted openings substantially in the direction of said antenna axis; and

a plurality of peripheral openings disposed between said slotted openings and said peripheral edge, said peripheral openings extending through said conductive layer and said substrate and attenuating surface waves within said substrate.

* * * * *

US006466177B1

(12) **United States Patent**
Kunysz

(10) **Patent No.: US 6,466,177 B1**
(45) **Date of Patent: Oct. 15, 2002**

(54) **CONTROLLED RADIATION PATTERN ARRAY ANTENNA USING SPIRAL SLOT ARRAY ELEMENTS**

(75) Inventor: **Waldemar Kunysz**, Calgary (CA)

(73) Assignee: **NovAtel, Inc.**, Calgary (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/915,112**

(22) Filed: **Jul. 25, 2001**

(51) **Int. Cl.**[7] **H01Q 13/12**; H01Q 13/10

(52) **U.S. Cl.** **343/769**; 343/770; 343/895

(58) **Field of Search** .... 343/700 MS, 770, 343/895, 767, 769

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,925,784 A	*	12/1975	Phelan	343/754
4,032,921 A	*	6/1977	Sikina, Jr. et al.	343/895
5,146,234 A		9/1992	Lalezari	343/895
5,175,561 A		12/1992	Goto	343/769
5,307,077 A	*	4/1994	Branigan et al.	343/720
5,581,268 A		12/1996	Hirshfield	343/853
5,621,422 A	*	4/1997	Wang	343/895
5,694,416 A		12/1997	Johnson	375/206
5,815,122 A		9/1998	Nurnberger et al.	343/767
5,940,037 A		8/1999	Kellerman et al.	343/700 MS
5,955,987 A		9/1999	Murphy et al.	342/357.06
5,995,044 A		11/1999	Junysz et al.	342/363
6,037,903 A		3/2000	Lange et al.	343/700 MS
6,081,239 A		6/2000	Sabet et al.	343/753
6,128,557 A		10/2000	Fenton et al.	701/13
6,208,313 B1		3/2001	Frank et al.	343/853
6,219,373 B1		4/2001	Lee et al.	375/130
6,225,959 B1		5/2001	Gordon	343/769
6,232,920 B1		5/2001	Brookner et al.	342/372
6,236,367 B1		5/2001	Du Toit et al.	343/700 MS
2001/0048399 A1	*	12/2001	Oberschmidt et al.	343/770

OTHER PUBLICATIONS

Xian Hua Yang, Characteristics of Aperture Coupled Microstrip Antenna with Various Radiating Patched and Coupling Apertures, IEEE Transactions on Antennas and Propagation, Jan. 1995.

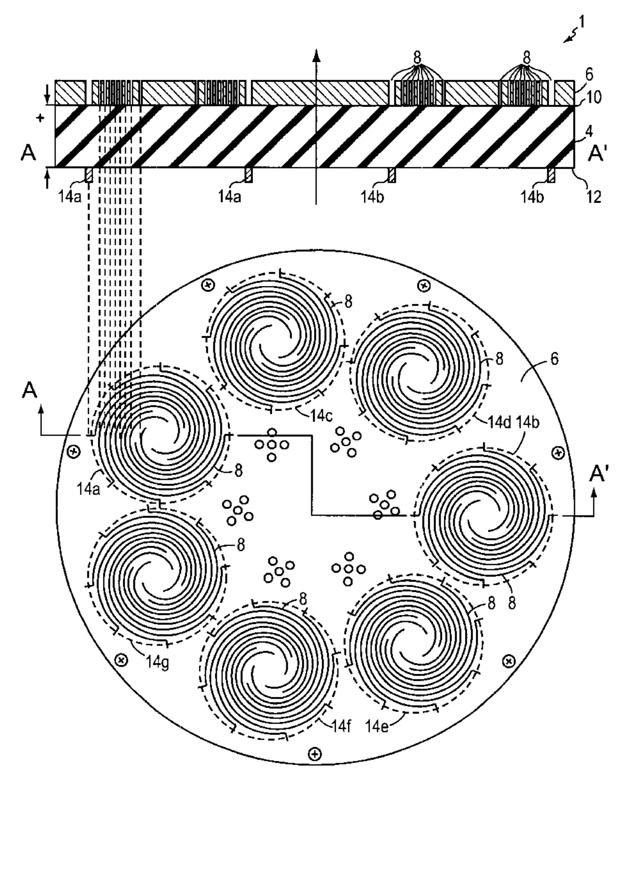
(List continued on next page.)

Primary Examiner—Don Wong
Assistant Examiner—Hoang Nguyen
(74) *Attorney, Agent, or Firm*—Cesari and McKenna, LLP

(57) **ABSTRACT**

A planar, controlled radiation pattern array antenna using spiral slot antenna arrays is disclosed. The CRPA antenna includes a nonconductive planar substrate with a plurality of transmission lines disposed on one surface. A conductive layer on the other surface of the substrate includes a plurality of slotted openings that form spiral slot array antennas such that each spiral slot array antenna opposed to a transmission line on the opposite side of the substrate.

11 Claims, 7 Drawing Sheets



OTHER PUBLICATIONS

Eli Aloni, Analysis of Dual Circularly Polarized Microstrip Antenna Fed by Crossed Slots, IEEE Transactions on Antennas and Propagation, Aug. 1994.

J.J. Picazo, On the Design of Nonuniformly Spaced Slot Arrays, IEEE Transactions on Antennas and Propagation, Nov. 1990.

Alison Brown, Kinematic Test Results of a Miniaturized GPS Antenna Array with Digital Beamsteering Electronics, ION NTM 2000, Jan. 2000.

A.J. Mac Millan, Cape—CRPA Associated Position Errors, ION NTM 2000, Jan. 2000.

Drew Williams, Four–Element Adaptive Array Evaluation fo United States Navy Airborne Applications, ION GPS 2000, Sep. 2000.

Basrur Rao, Chracterizing the Effects of Mutual Coupling on the Performance of a Miniturized GPS GPS Adaptive Antenna Array, ION GPS 2000, Sep. 2000.

Charles Manry Jr. Advanced Mini Array Antenna Design Using High Fidelity Computer Modeling and Simulation, ION GPS 2000, Sep. 2000.

Alison Brown, Test Results of Digital Beamforming GPS Receiver for Mobile Applications, ION NTM 2000, Jan. 2000.

D.M. Pozar, Reciprocity Method of Analysis for Printed Slot and Slot–Coupled Microstrip Antennas, IEEE Transactions on Antennas and propagation, Dec. 1986.

* cited by examiner

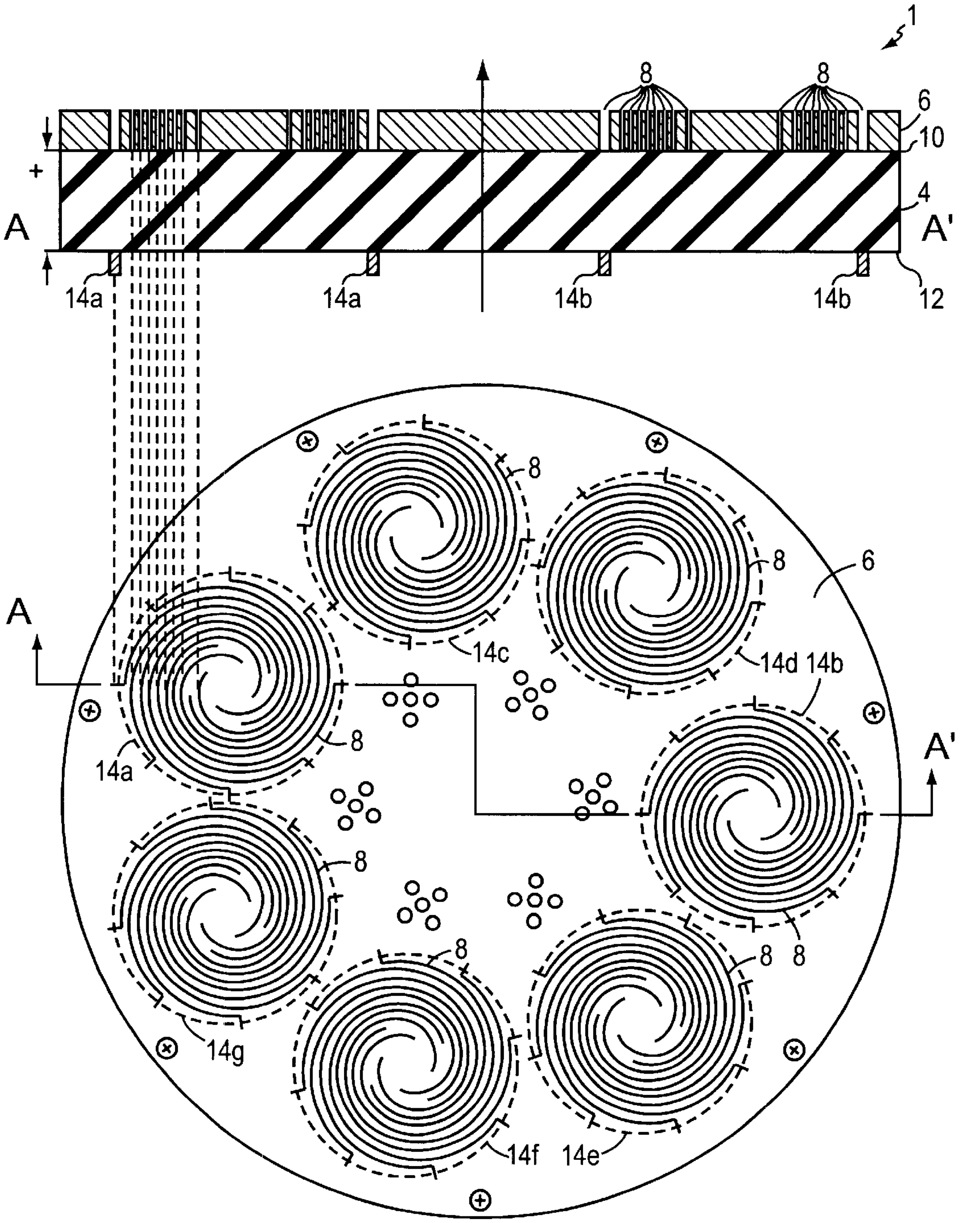

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FIG. 1

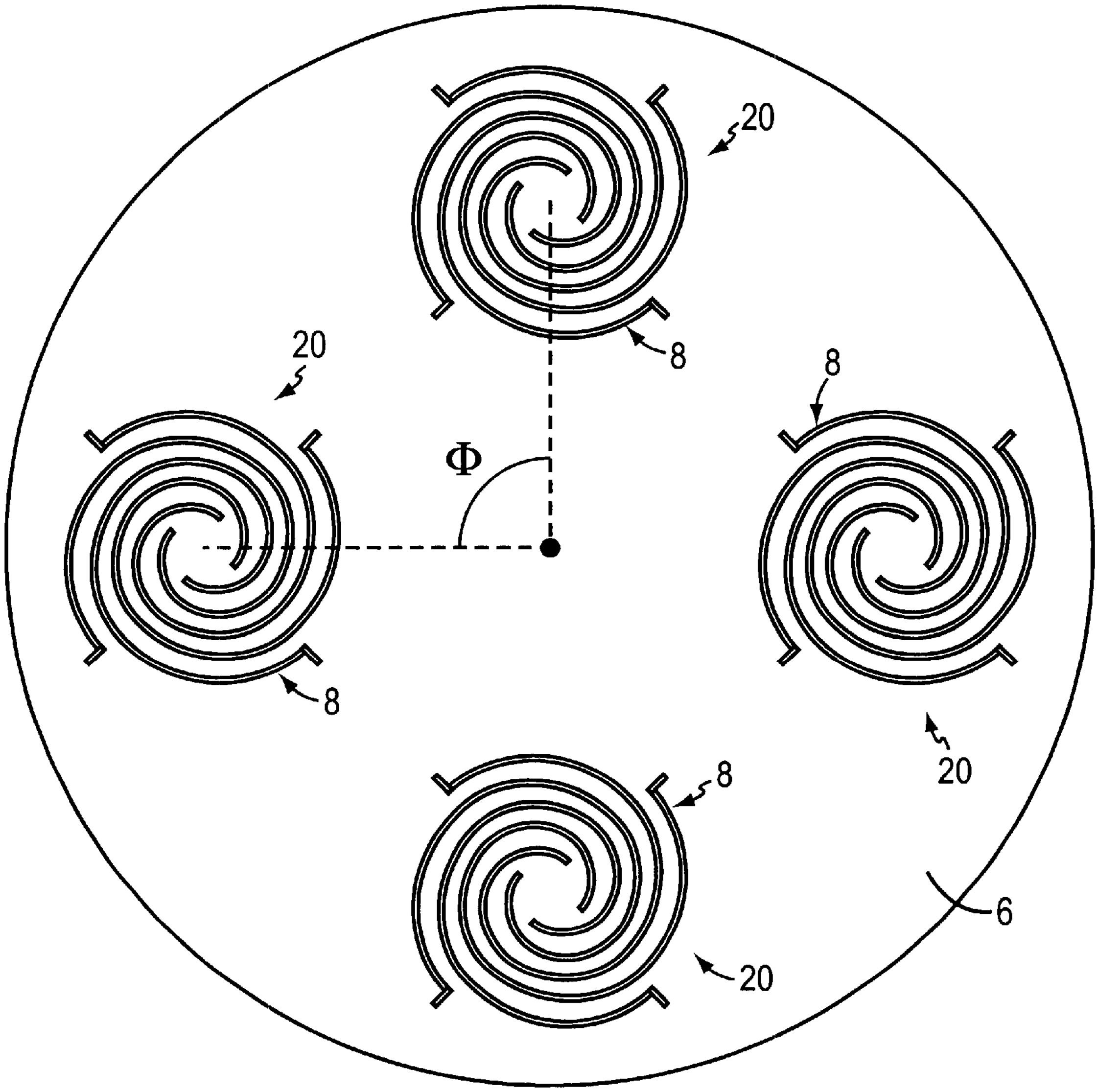
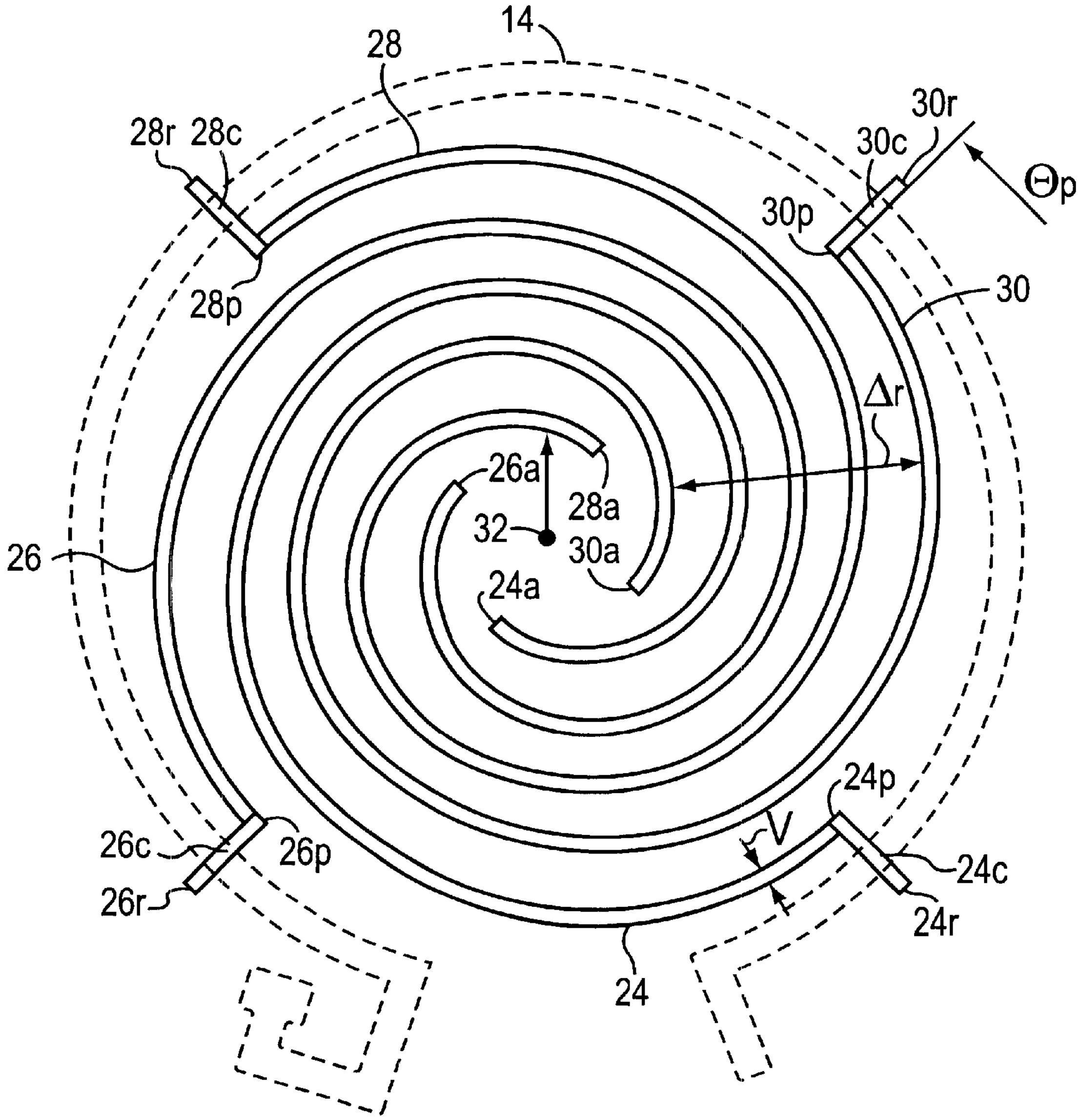


FIG. 2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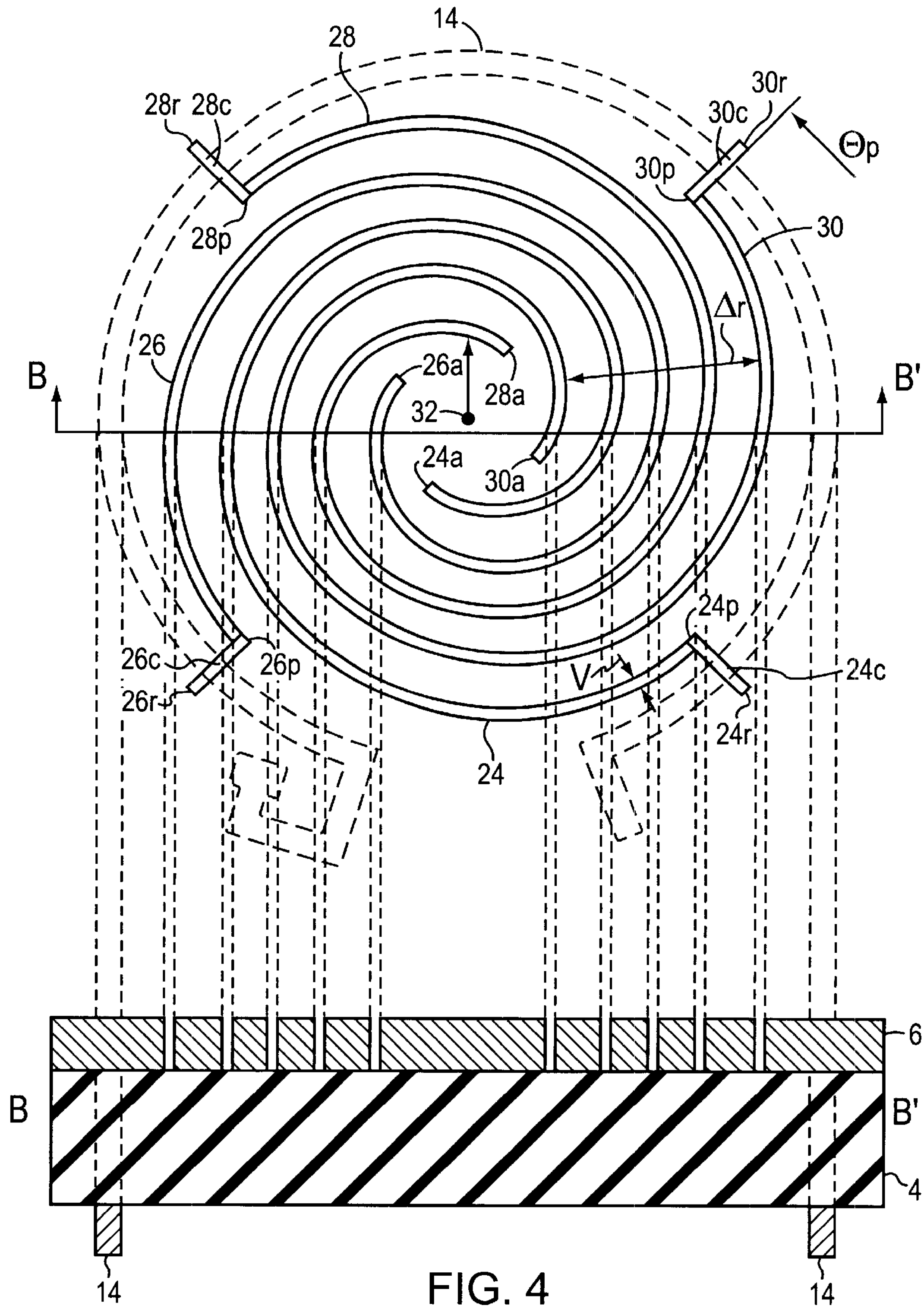
24r
24

FIG. 3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28p
30r
30c
30p
Θp
30
Δr
26
B
B'
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32
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14
14

FIG. 4

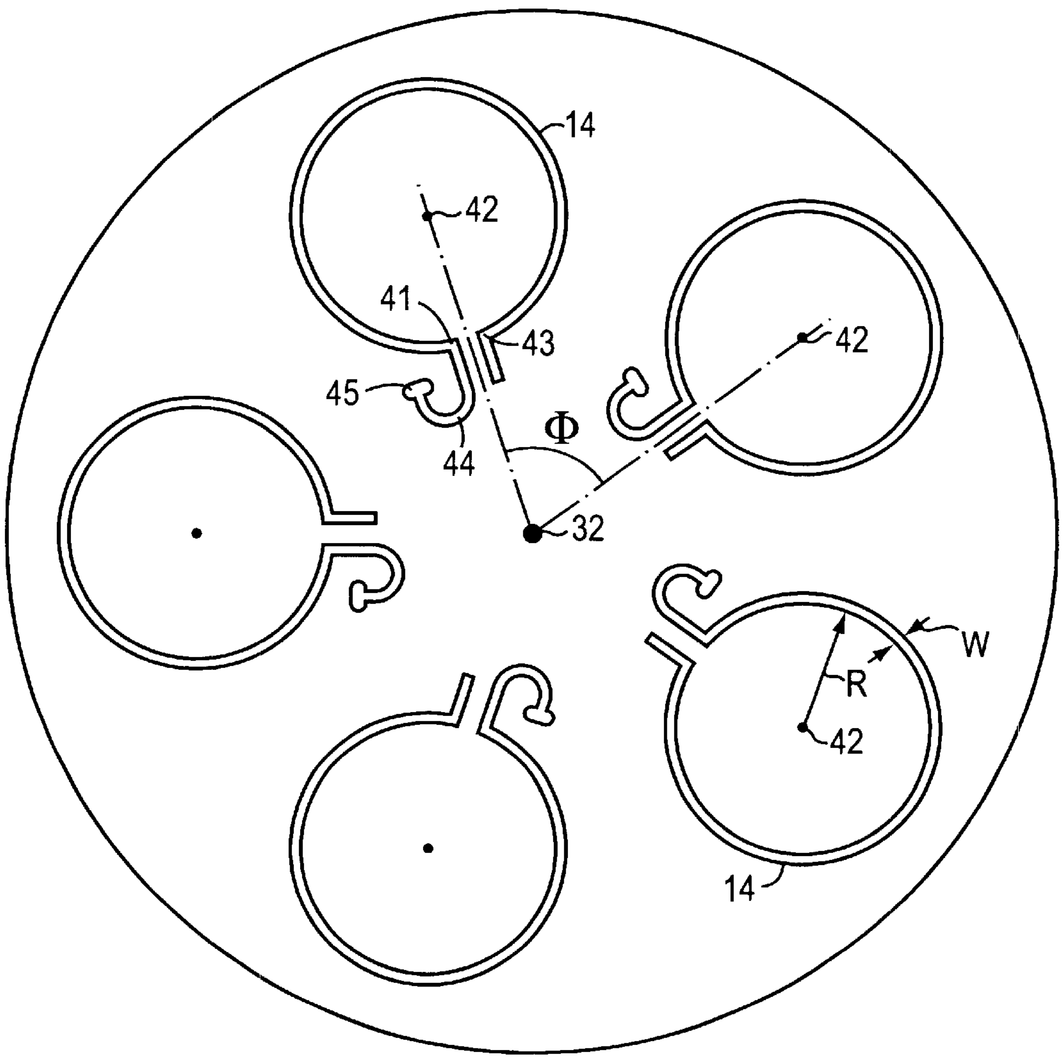


FIG. 5

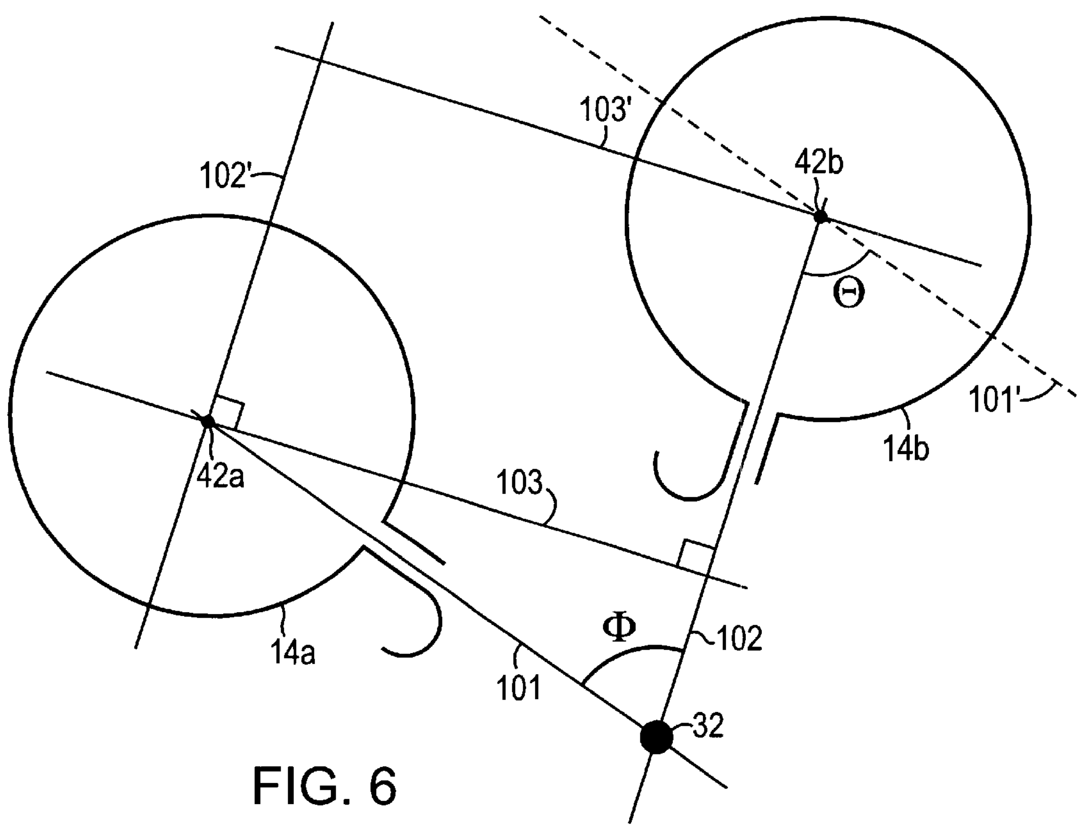


FIG. 6

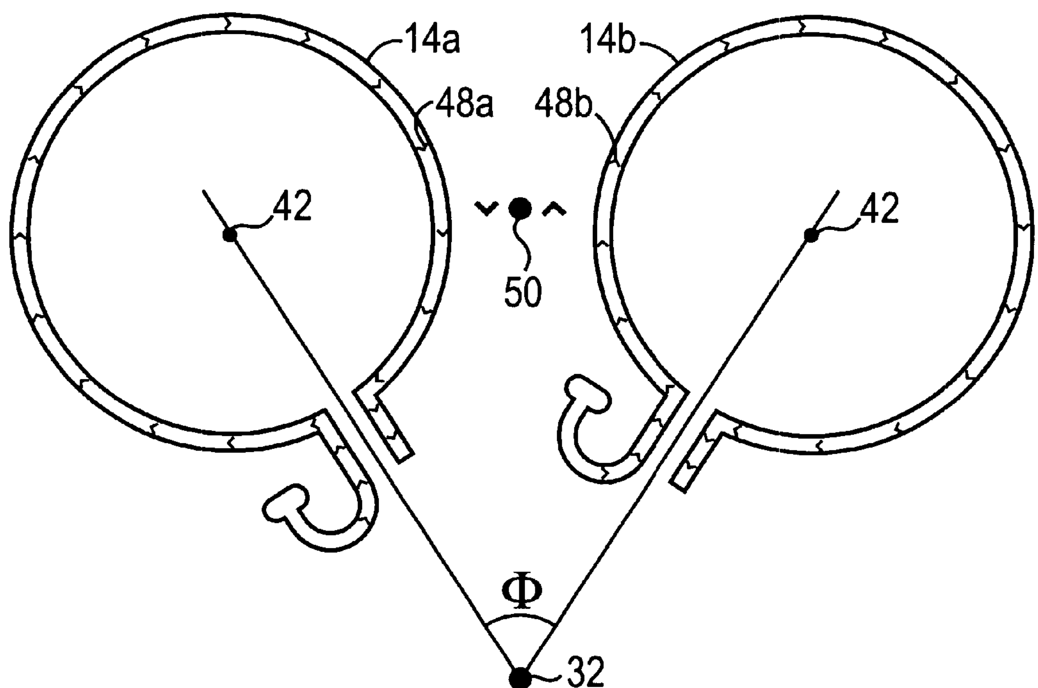


FIG. 7

CONTROLLED RADIATION PATTERN ARRAY ANTENNA USING SPIRAL SLOT ARRAY ELEMENTS

FIELD OF THE INVENTION

The present invention is related to planar broadband array antennas and, more particularly, to controlled radiation pattern array antennas.

BACKGROUND OF THE INVENTION

Controlled Radiation Pattern Antennas (CRPA) are known in the art. A CRPA operates by using spatial filtering techniques to steer nulls in the antenna radiation pattern towards sources of interference. A CRPA is normally an array antenna comprised of a plurality of antenna elements. By controlling the phase gradients between antenna elements, the radiation pattern of the antenna can be controlled.

In prior art implementations of controlled radiation pattern atnennas, stacked patch dipole antennas are used as the array elements. U.S Pat. No. 5,955,987, granted to Murphy, et al, for example, discloses a CRPA antenna using three dipole antenna patches. U.S. Pat. No. 6,052,086, granted to Kudoh discloses an array antenna having a plurality of dipole patches on one side of a baseboard.

A four element controlled radiation pattern antenna using stacked patch dipole antennas is described in "Characterizing the Effects of Mutual Coupling on the Performance of Miniaturized GPS Adaptive Antenna Array" by Basrur Rao et al, ION GPS 2000, pages 2491–2498.

It is often desirable to be able to mount a controlled radiation pattern antenna on a vehicle. Many receivers for the global positioning system (GPS) utilize controlled radiation pattern antennas to reduce the effects of multipath or other interfering signals. However, many CRPAs are physically too large to fit within given form factors required by the host vehicle. Reduction in size of the antenna is possible, but this reduction in size brings the antenna elements closer together, thereby causing an increase in mutual coupling, which can negatively affect the performance of the array.

While the art describes controlled radiation pattern antennas, there remains a need for improvements that offer advantages and capabilities not found in presently available devices. Specifically, CRPA antennas are often larger than is desirable. Additionally, mutual coupling between adjacent antenna elements often reduces the performance of the antenna.

There is needed a CRPA antenna that can be made physically smaller, and there is a further need to reduce mutual coupling between adjacent antenna elements to improve antenna performance.

SUMMARY OF THE INVENTION

A controlled radiation pattern array antenna uses spiral slot array elements. The antenna comprises a substantially planar dielectric substrate having a first surface and a second surface. A conductive layer having a plurality of similar curved slotted openings is disposed on the first surface. The curved slotted openings form a plurality of spiral slot array antennas. The spiral slot array antennas are located such that the angle Φ between any two adjacent spiral slot array antennas with respect to the center of the antenna is equal to 2π/N, wherein N is the number of spiral slot array antennas.

A plurality of transmission lines is disposed on the second surface of the antenna with each transmission line being aligned with a corresponding spiral slot array antenna on the first surface. Each antenna element comprising of the spiral slot array and the transmission line located underneath is rotated about its center such that adjacent antenna elements are rotated by 2π/N with respect to each other. The rotation of 2π/N between adjacent elements randomizes the pattern error of each individual element yielding a very uniform radiation pattern of a combined array of all antenna elements.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of which:

FIG. **1** is a top view of an antenna according to an illustrative embodiment of this invention and a cross-sectional view of the antenna through line A—A';

FIG. **2** is a planar view showing the first surface of a CRPA antenna having a plurality of spiral slot array antenna elements;

FIG. **3** is a planar view of an illustrative spiral slot array antenna;

FIG. **4** is a planar and cross-sectional view of an illustrative spiral slot array antenna;

FIG. **5** shows the second surface of a CRPA antenna having a plurality of transmission lines disposed on the second surface;

FIG. **6** shows the rotation of a transmission line relative to any adjacent transmission line;

FIG. **7** shows the current flows through adjacent transmission lines.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

FIG. **1** shows a top and cross-sectional view of a controlled radiation pattern antenna **1** in accordance with an illustrative embodiment of this invention. The cross sectional view is taken along line A—A' of the top view. The antenna comprises a substantially planar substrate **4** of nonconductive or dielectric material having a thickness t, with a conductive layer **6** having a plurality of curved slotted openings **8** disposed on a first surface **10** and a plurality of transmission lines **14** disposed on a second surface **12**. On the top view, transmission lines **14*a***, **14*b***, **14*c***, **14*d***, **14*e***, **14*f*** and **14*g*** are shown in shadow, as they are disposed on the second surface of the antenna.

Any dielectric material may be used for the substrate **4**. In a preferred embodiment, the substrate is RO3006™ available from Rogers Corporation of Chandler, AZ. It should be noted that it is expressly contemplated that other substrates may be utilized in accordance with this invention.

As is well known in the relevant art, the size of the antenna will be affected by the dielectric constant of the choice of substrate. A substrate **4** having a higher dielectric constant will enable one to make the antenna physically smaller. Conversely, a substrate **4** with a lower dielectric constant will cause the antenna to be physically larger. There are disadvantages to using higher dielectric materials. As those skilled in the art know, the higher the dielectric constant of a substrate used in an antenna, the narrower the bandwidth of the antenna. Conversely, by using a lower dielectric constant material, the antenna's bandwidth will be wider, but the physical size will also increase. The invention can utilize a substrate having any dielectric constant, with the substrate chosen to allow the antenna to conform to either the requisite form factor or bandwidth as desired.

In an illustrative embodiment, antenna **1** may be fabricated from a two-layer printed circuit board (PCB), where the transmission lines **14** and the slotted openings **8** can be formed by suitably etching portions of the respective cladding layers to form the slotted openings **8** and the transmission lines **14**. Transmission line **14** shall stand for any transmission line **14***a*, **14***b*, **14***c*, **14***d*, **14***e*, **14***f* and **14***g*.

FIG. **2** is a view the first surface **10** of an illustrative embodiment of a CRPA antenna **1** using spiral slot array antenna elements. A conductive layer **6** covers the first surface **10** of the substrate **4**. The conductive layer **6** includes a plurality of similar curved, slotted, openings **8** where each slotted opening extends through the conductive layer **6** to the front surface of the substrate **4**. The plurality of curved, slotted openings **8** form spiral slot array antennas **20** (SSAA) which are further described below. The antenna **1** is thus an array of arrays, with the antenna **1** comprising a plurality of spiral slot array antennas **20** and each spiral slot array antenna **20** comprising a plurality of spiral slot antennas.

Each SSAA **20** is located so that angle ϕ between any SSAA **20** and an adjacent SSAA **20** is $2\pi/N$ radians with respect to the antenna center **16**, wherein N is the number of spiral slot array antennas. Thus, in this illustrative embodiment, $\phi=\pi/2$.

The curved slotted openings **8** can be any shaped spiral, including a conical section (i.e., a circular, elliptical, parabolic, or hyperbolic arc), an Archimedean spiral, a logarithmic spiral, or an exponential spiral. The spirals could even be of a free-hand type. The only constraint to a free-hand curve is that the length of the curve must be accurately determined in order for it to resonate at the desired frequency. Spiral slots are used to maintain constant spacing between adjacent elements at a given distance from the center. This constant distance minimizes cross-coupling and radiation of unwanted cross-polarized signals.

FIG. **3** shows an illustrative SSAA **20** in greater detail from the top. Reference is made to U.S. patent application Ser. No. 09/375,319, filed Aug. 16, 1999 entitled "Aperture Coupled Slot Array Antenna" which teaches spiral slot array antennas and which is hereby incorporated by reference.

SSAA **20** is comprised of slots **24**, **26**, **28** and **30**. The slots have respective axial ends **24***a*, **26***a*, **28***a* and **30***a* proximate the SSAA center **32**, and respective peripheral ends **24***p*, **26***p*, **28***p* and **30***p*. Each peripheral end is connected to a radiating slot line **24***r*, **26***r*, **28***r* and **30***r* respectively. Radiating slot lines **24***r*, **26***r*, **28***r* and **30***r* are situated such that they are perpendicular to transmission line **40** (shown in shadow) which is disposed on the second surface of the substrate.

Accordingly, when the antenna is used to transmit signals, electromagnetic energy is fed into the transmission line **14**, which is located on the back surface of the substrate, and is electromagnetically coupled to the slotted openings **24**, **26**, **28** and **30**, which are on the front surface of the antenna. This coupling occurs at the four respective coupling regions **24***c*, **26***c*, **28***c* and **30***c* where the radiating slot lines **24***r*, **26***r*, **28***r* and **30***r*, which lie on the front surface, are located most proximate to and directly opposite the transmission line **40** which lies on the back surface of the substrate. It should be expressly noted that in the invention, the transmission lines encircle the majority of the spiral slot array antennas, which is unlike the SSAA taught by the incorporated patent. Additionally, the referenced patent does not teach the use of radiating slot lines that are perpendicular to the transmissions lines. By being perpendicular, the radiating slot lines couple with the transmission line better than if they "crossed" at any other angle.

For example, a portion of the radiating slot lines **24***r*, **26***r*, **28***r* and **30***r* are located a distance equivalent to the substrate thickness t from the transmission line at coupling regions **24***c*, **26***c*, **28***c* and **30***c*. As is well known in the relevant art, the electromagnetic energy passing through transmission line **40** will produce a radiating field across the radiating slot lines **24***r*, **26***r*, **28***r* and **30***r* in the coupling regions **24***c*, **26***c*, **28***c* and **30***c*. This electromagnetic energy will be similarly transferred into the slotted openings **24**, **26**, **28** and **30** from the radiating slot lines coupling regions **24***r*, **26***r*, **28***r* and **30***r* respectively.

The degree of coupling is a function of the thickness t of the substrate, the width w of the transmission line, the width v of the slotted opening, and the dielectric properties of the substrate. Conversely, when the antenna is used to receive signals, radiation energy is received at the slotted openings **24**, **26**, **28**, **30** is transferred into the radiating slot lines **24***r*, **26***r*, **28***r* and **30***r*. From the radiating slot lines **24***r*, **26***r*, **28***r* and **30***r*, the electromagnetic energy is then coupled into the transmission line **40** at the coupling regions **24***c*, **26***c*, **28***c* and **30***c*.

Unwanted cross-polarization is minimized by keeping the opening width v narrow in comparison to the guided wave length L_{gw}. The shape of each of the slotted openings, from the axial end to the peripheral end, can be described best in polar coordinates using the antenna axis **32** as origin. The radial distances $R(\theta)$ of the interior edges of the slotted openings increase from r_a at the respective axial, to a maximum radius of r_p at the respective peripheral. The radial distance from the antenna axis to the inside edge of any of the slotted opening increases with the polar angle θ and is also a function of the interval spacing Δr for each spiral-shaped slotted opening where $\Delta r \equiv r(\theta+2\pi)-r(\theta)$. For the slotted opening, the radial distance from the antenna axis can be described by means of the equation,

$$r(\theta,\Delta r)=r_a+\Delta r(\theta/2\pi) \tag{1}$$

Each slotted opening is spatially offset from each adjacent opening by $2\pi/N$ radians. Thus, in this illustrative embodiment, each opening is offset by $\pi/2$ radians. The guided wave length of each of the slotted openings is specified to be a multiple of quarter-wavelengths of the receiving or transmitting signal in order to maximize the antenna efficiency

$$\left(\text{i.e., } L_{GW}=\frac{n\lambda}{4}\right).$$

In the configuration shown, each spiral-shaped slotted openings **24**, **26**, **28**, **30** subtends an angle of θ_p, where

$$\frac{n\lambda}{4}=\int_0^{\theta_p}\left(\frac{\Delta r}{2\pi}\sqrt{1+\theta^2}\right)d\theta \tag{2}$$

The width v of each of the slotted openings **24**, **26**, **28**, **30** is specified to be substantially smaller than the guided wave length and large enough to enable good electromagnetic coupling between the respective slotted opening **24**, **26**, **28**, **30** and a transmission line **40**. Methods of optimizing the width and wavelength to create good electromagnetic coupling are well known in the art. These methods are described in J. J. Gonzalez Picazo, "On the Design of Nonuniformly Spaced Slot Arrays," IEEE Transactions on Antennas and Propagation, Vol. 38, no. 11, pp. 1780–1783, 1990; Eli Aloni, "Analysis of a Dual Circularly Polarized Microstrip

Antenna Fed by Crossed Slots," IEEE Transactions on Antennas and Propagation, vol. 42, no. 8, pp. 1053–1058, 1994; David Pozar, "Reciprocity Method of Analysis for Printed Slot and Slot-Coupled Microstrip Antennas," IEEE Transactions on Antennas and Propagation, vol. 34, no. 12, p1439, 1986; and Xian Yang, "Characteristics of Aperture Coupled Microstrip Antennas with Various Radiating patches and Coupling Apertures," IEEE Transactions on Antennas and Propagation, vol. 43, no. 1, 1995 which are hereby incorporated by reference.

The transmission line **40** "crosses" each of the slotted openings **24**, **26**, **28**, **30** at respective coupling regions **24***c*, **26***c*, **28***c* and **30***c*. The coupling regions **24***c*, **26***c*, **28***c* and **30***c* are offset by $2\pi/N$ radians from one another. This configuration provides for matching the electrical phase differences in the coupling regions (i.e., in this illustrative embodiment the differences are 90°) with the spatial differences of the slotted openings when the guided wave length of the transmission line is tuned to be one wavelength λ_1.

FIG. **4** is a cross-sectional and top view of an illustrative spiral slot array antenna. The cross sectional view along line B—B' shows the slotted openings **24**, **26**, **28** and **30** are cut into the conductive layer **6** which is disposed on the first surface of the substrate **4**. The transmission line **14**, which is shown in shadow in the top view, is disposed on the second surface of the conductive layer **4** in the cross-sectional view.

FIG. **5** is a view of the second surface **12** of an antenna **1** according to an illustrative embodiment of this invention. Transmission lines **14** are disposed on the second surface **12** such that the center **42** of each transmission line is aligned with a center **22** of a SSAA **20** on the first surface **10** of the antenna. Thus angle ϕ, the angle between any two adjacent transmission lines **14** with respect to the antenna center **32**, is the same as the angle between any two adjacent SSAAs **20** on the first surface **10** of the antenna **1**. Angle $\phi=2\pi/N$, wherein N is the number of SSAAs **20** in the antenna **1**. Thus, in this illustrative embodiment $\phi=\pi/2$.

A connector **45** is electrically connected to a first conductive lead **44** and to an input end **41** of transmission line **14**. A second conductive lead **46** is electrically connected to load impedance **48** and to a terminal end **43** of transmission line **40**. The transmission lines **14** are in the shape of a circular arc, where an inside edge of the transmission line lies at a radius of R and an outside edge lies at a radius of R+w from the transmission line center **42**. The length of the transmission line **40** measured from the input end to the terminal end should be equal to the desired wavelength.

Additionally, each transmission line **14** is rotated about its transmission line center **42** with respect to an adjacent transmission line **14**. This rotation around transmission line center **42** is shown in FIG. **6**. Transmission lines **14***a* and **14***b* have centers **42***a* and **42***b* respectively. Radii **101** and **102** form angle ϕ. Line **101**' is parallel to radius **101**. Lines **103** and **103**' are parallel, as are lines **102** and **102**'. Line **102** is perpendicular to line **103**. The angle θ formed by line **101**' and radius **102** is the angle of rotation of transmission line **14***b* with respect to transmission line **14***a*. In a preferred embodiment $\theta=2\pi/N$. Additionally, the corresponding SSAA on the first surface is also rotated about its center by the same amount. Thus, each element, including the transmission line and the spiral slot array antenna, is rotated around its center θ, wherein in a preferred embodiment $\theta=2\pi/N$.

When $\theta=\phi$, the electric current in the transmission lines flows in opposite directions in adjacent elements. FIG. **7** shows this current flow. In transmission line **14***a*, current **48***a* enters the input end **41***a* via connector **45***a* and first conductive lead **46***a*. Current **48***b* enters transmission line **40***b* via the input end **41***b* via connector **45***b* and first conductive lead **46***b*. At point **50**, the closest that transmission line **14***a* and **14***b* are located, currents **48***a* and **48***b* are flowing in opposite directions. This arrangement reduces mutual coupling between adjacent antenna elements, enabling a smaller physical antenna in accordance with this invention.

While the invention has been described with reference to particular embodiments, it will be understood that the present invention is by no means limited to the particular constructions and methods herein disclosed and/or shown in the drawings, but also comprises any modifications or equivalents within the scope of the claims. Specifically, it is expressly contemplated that other numbers of spiral slot array antennas may be used as antenna elements. It is also expressly contemplated that each spiral slot array antenna may have other numbers of spiral slot antenna elements. As an illustrative example, it is expressly contemplated that an antenna in accordance with this invention has nine spiral slot array antennas as elements, with each SSAA having six spiral slot antennas.

What is claimed is:

1. A controlled radiation pattern array antenna, the antenna comprising:

a substantially planar dielectric substrate having a front surface and a back surface;

a conductive layer disposed on the front surface;

a plurality of similar curved, slotted openings extending through the conductive layer to the substrate, the slotted openings forming a plurality of spiral slot arrays;

a plurality of transmission lines disposed on the back surface of the substrate such that the transmission lines are aligned with the spiral slot arrays.

2. The antenna of claim **1** further comprising:

a dielectric substance filling the curved, slotted openings.

3. The antenna of claim **1** wherein each of the plurality of curved slotted openings further comprises:

a shape selected from the group consisting of a conical-section arc, a spiral arc, a logarithmic arc, and an exponential arc.

4. The antenna of claim **1** wherein each antenna element comprising of one of the spiral slot arrays and its corresponding transmission line forms a portion of an arc surrounding a center wherein each antenna element is rotated around its center by $2\pi/N$ with respect to the orientation of an adjacent antenna element, wherein N is the number of spiral slot array antennas elements.

5. The antenna of claim **1** wherein the spiral slot array antennas are located such that the angle between any two adjacent spiral slot array antennas with respect to the antenna center is $2\pi/N$.

6. The antenna of claim **1** wherein each spiral slot array antenna further comprises:

a plurality of spiral slot antennas;

each spiral slot antenna having a radiating slot line extending radially from an end of the spiral slot antenna farthest from the antenna center such that the radiating slot line is substantially perpendicular to a transmission line.

7. The antenna of claim **1** wherein each transmission line is rotated around its center by $2\pi/N$ with respect to the orientation of an adjacent transmission line, wherein N is the number of spiral slot array antennas and wherein the spiral slot array antennas are located such that the angle between any two adjacent spiral slot array antennas with respect to the antenna center is $2\pi/N$.

8. A controlled radiation pattern array antenna, the antenna comprising: a substantially planar dielectric substrate having a front surface and a back surface containing an antenna center;

a conductive layer, the conductive layer being disposed on the front surface of the substrate;

a plurality of similar curved, slotted openings extending through the conductive layer to the substrate, the openings forming a plurality of spiral slot array antennas;

a plurality of transmission lines, the transmission lines being disposed on the back surface of the substrate such that the transmission lines are aligned with the spiral slot array antennas;

each transmission line forming a portion of an arc of radius R surround a transmission line center,

each transmission line being rotated around its center by $2\pi/N$ with respect to the orientation of an adjacent transmission line, wherein N is the number of spiral slot array antennas, and

the spiral slot array antennas located such that the angle between any two adjacent spiral slot array antennas with respect to the antenna center is $2\pi/N$.

9. A spiral slot array antenna, the antenna comprising:

a substantially planar nonconductive substrate having a first surface and a second surface and containing an antenna center;

a conductive layer disposed on the first surface of the substrate; a transmission line forming a portion of an arc centered on the antenna center and having a first end and a second end disposed on the second surface of the substrate, the first end connected to a first conductive lead, the first conductive lead connected to a connector, the second end connected to a second conductive lead, the second conductive lead connected to a terminal impedance;

a plurality of curved, slotted openings extending through the conductive layer to the first surface substrate, the openings forming a plurality of spiral slot antennas centered on the antenna center, wherein each spiral slot antenna has a radiating slot line extending radially away from an end of the spiral slot antenna furthest away from the antenna center such that each radiating slot line is substantially perpendicular to the transmission line.

10. An antenna array, the antenna array comprising:

a substantially planar dielectric substrate having a front surface and a back surface;

a conductive layer disposed on the front surface;

a first array of a plurality or curved, slotted opening extending through the conductive layer to the substrate;

an array of the first arrays forming an antenna formed from an array of the first arrays; and

a plurality of transmission lines disposed on the back surface of the substrate such that the transmission lines are aligned with the first arrays.

11. A method for making a controlled radiation pattern antenna, the method comprising the steps of:

placing a conductive layer on a front surface of a substantially planar dielectric surface;

forming a first array of a plurality of curved, slotted openings extending through the conductive layer to the substrate; and

forming an array of the first arrays to form an antenna formed from an array of the first arrays.

* * * * *

US007250916B2

(12) United States Patent
Kunysz et al.

(10) **Patent No.: US 7,250,916 B2**
(45) **Date of Patent: Jul. 31, 2007**

(54) **LEAKY WAVE ANTENNA WITH RADIATING STRUCTURE INCLUDING FRACTAL LOOPS**

(75) Inventors: **Waldemar Kunysz**, Calgary (CA); **Earl Badger**, Calgary (CA); **David Plamondon**, Calgary (CA)

(73) Assignee: **Novatel Inc.**, Alberta (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/184,676**

(22) Filed: **Jul. 19, 2005**

(65) **Prior Publication Data**

US 2007/0018899 A1 Jan. 25, 2007

(51) **Int. Cl.**
H01Q 13/10 (2006.01)
H01Q 1/38 (2006.01)
H01Q 1/36 (2006.01)

(52) **U.S. Cl.** .... **343/770**; 343/700 MS; 343/895

(58) **Field of Classification Search** .... 343/700 MS, 343/767, 770, 895
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,621,422	A *	4/1997	Wang	343/895
6,445,354	B1	9/2002	Kunysz	
6,452,560	B2	9/2002	Kunysz	
6,466,177	B1 *	10/2002	Kunysz	343/769
6,480,162	B2	11/2002	Sabet et al.	
6,642,898	B2 *	11/2003	Eason	343/770
2002/0067315	A1	6/2002	Kunysz et al.	

OTHER PUBLICATIONS

Nurnberger, M. W., et al., "A Planar Slot Spiral for Multi-Function Communications Apertures", Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, IEEE, 1998, pp. 774-777.
Nurnberger, M. W., et al., "New Techniques for Extremely Broadband Planar Slot Spiral Antennas", Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, IEEE, 1999, pp. 2690-2693.
Andersen, Lars and Volakis, John L., "Simulation of Linearly Tapered Slot Antennas Using an Adaptive Multi-Resolution FE/BI Approach", Radiation Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, IEEE, 2000, pp. 1180-1183.
Notification of Transmittal of the International Search Report and the Written Opinion of the International Searching Authority, or the Declaration. PCT/CA2006/001127. Nov. 2, 2006.

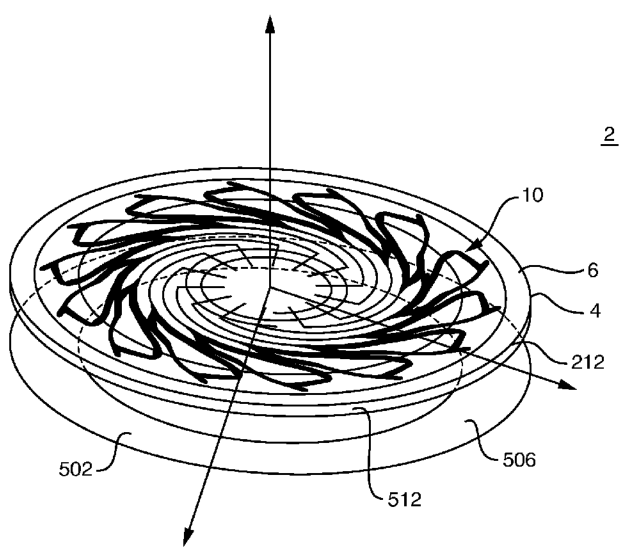
* cited by examiner

Primary Examiner—Shih-Chao Chen
(74) *Attorney, Agent, or Firm*—Cesari & McKenna, LLP

(57) **ABSTRACT**

An antenna is provided for acquiring RF signals from various satellite ranging systems including GPS, GLONASS, GALILEO and OmniSTAR®. The antenna configuration includes a radiating structure of multi-arm spiral slots terminated with fractal loops. A leaky wave microstrip spiral feed network is used to excite the radiating structure of the antenna. The fixed beam phased array of aperture coupled slots is optimized to receive a right hand polarized signal. The proposed antenna is made out of a single PCB board. The antenna has a very uniform phase and amplitude pattern in the azimuth plane from 1.15 to 1.65 GHz, therefore providing consistent performance at GPS, GLONASS, GALILEO and OmniSTAR® frequencies. The antenna also has a common phase center at the various frequencies from 1175 MHz to 1610 MHz and substantially the same radiation pattern and axial ratio characteristics.

20 Claims, 13 Drawing Sheets



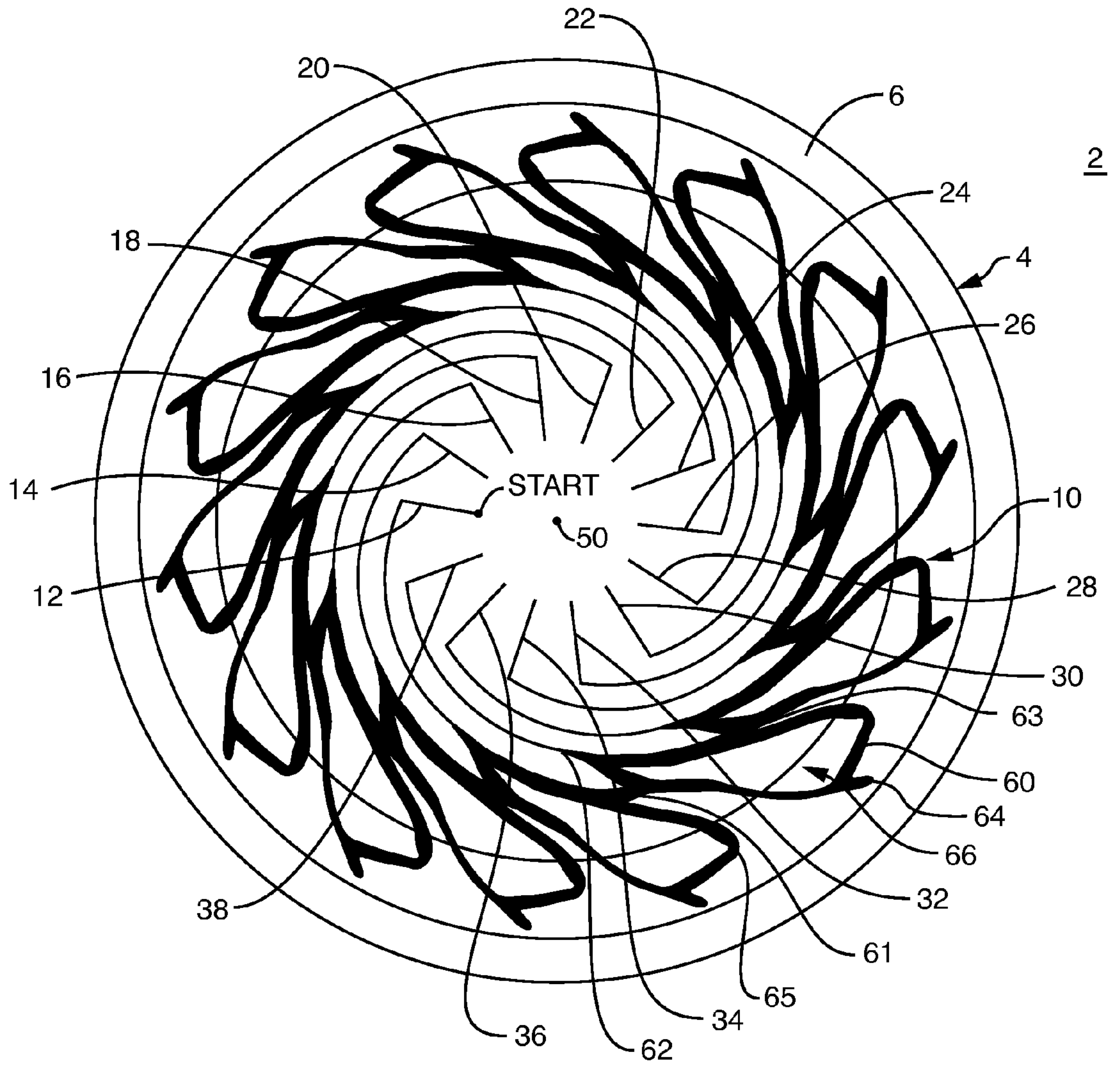

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FIG. 1

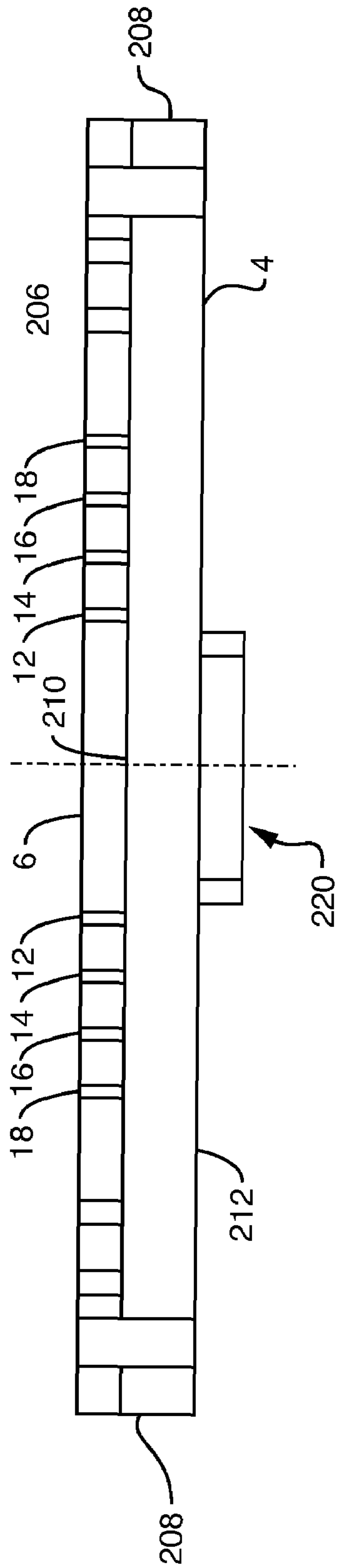


FIG. 2

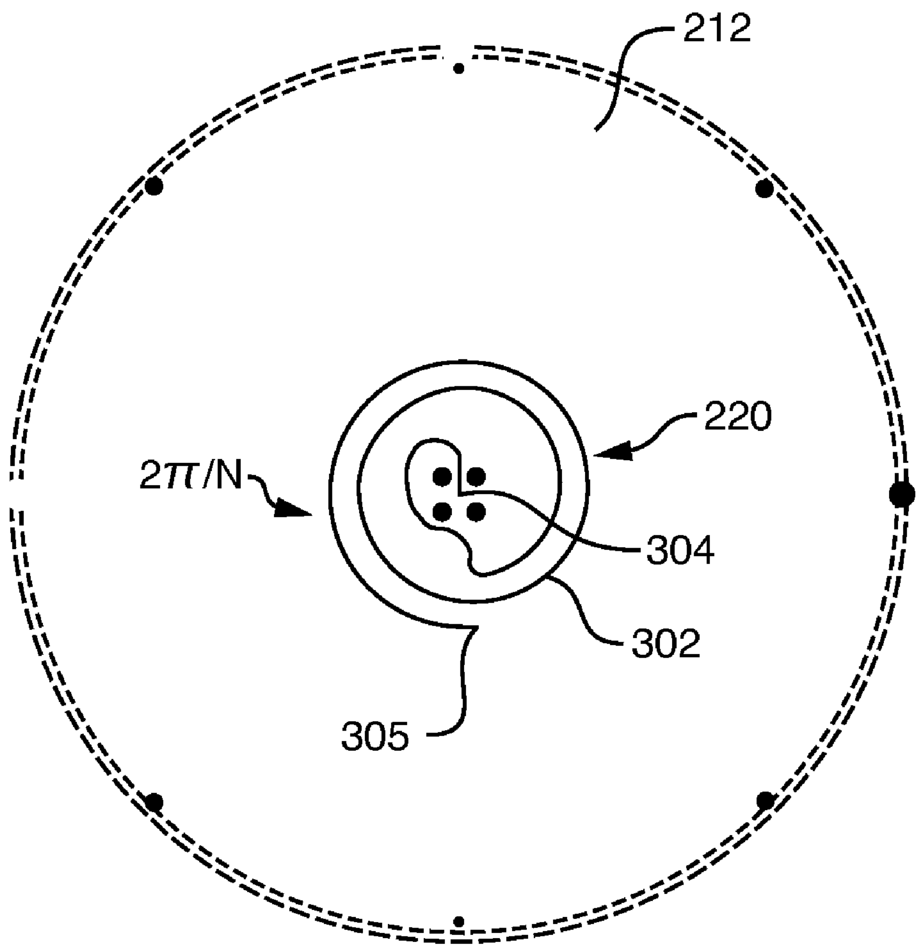


FIG. 3A

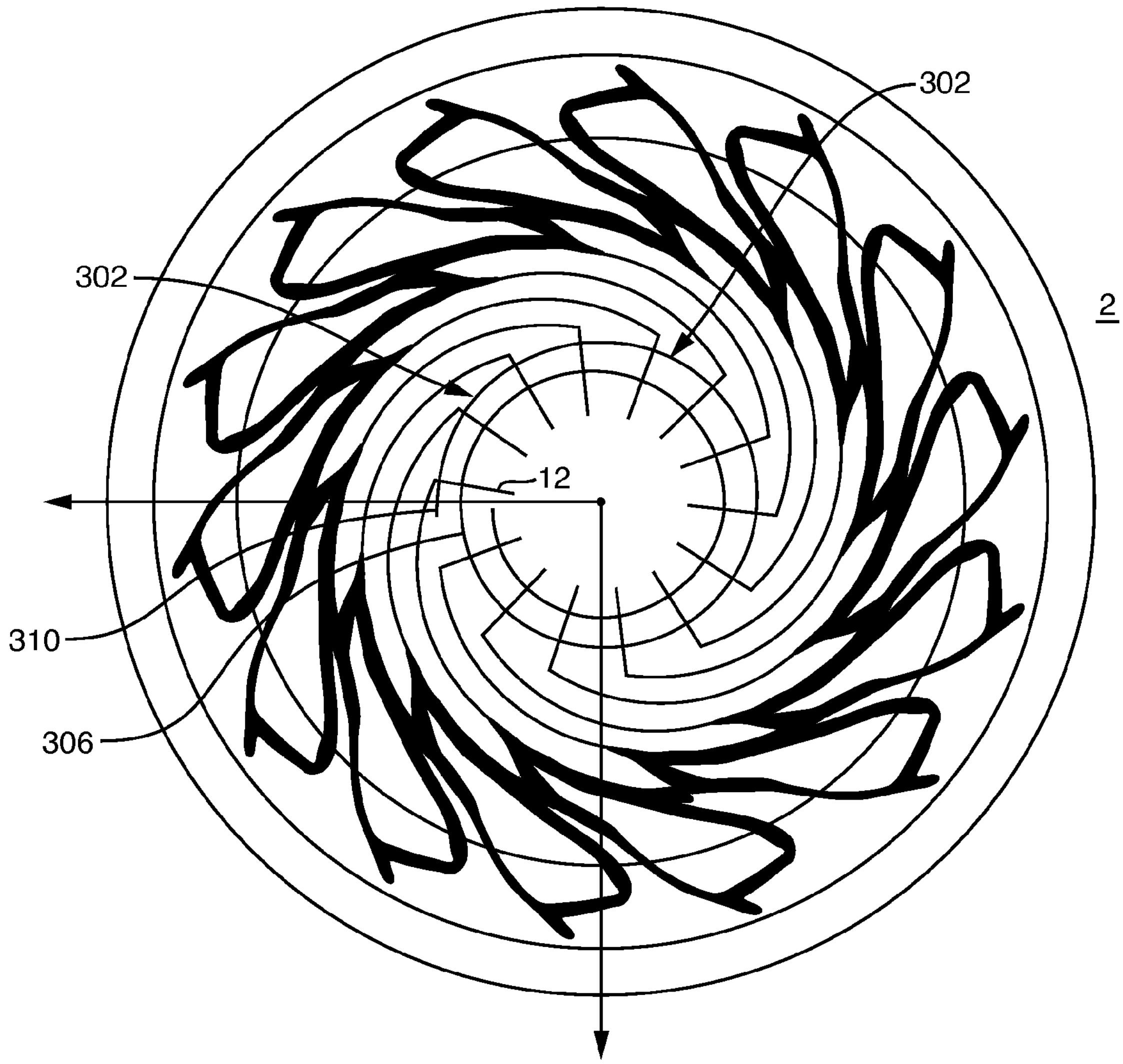


FIG. 3B

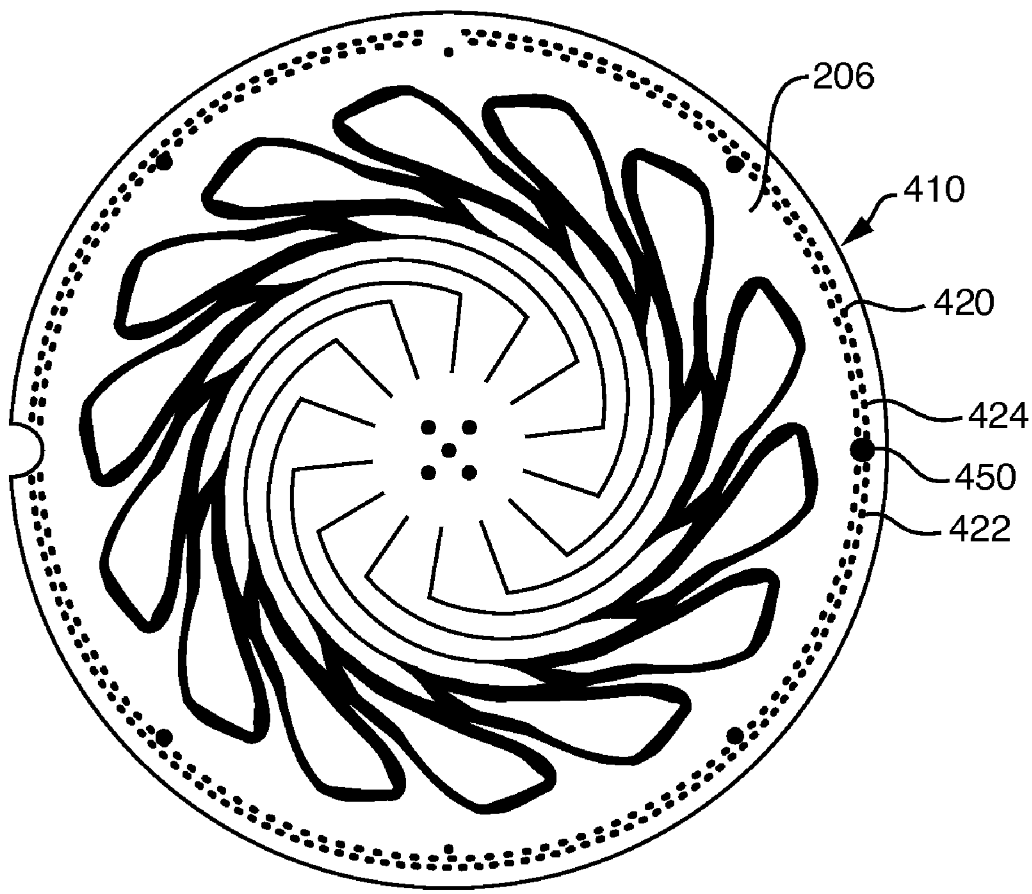


FIG. 4

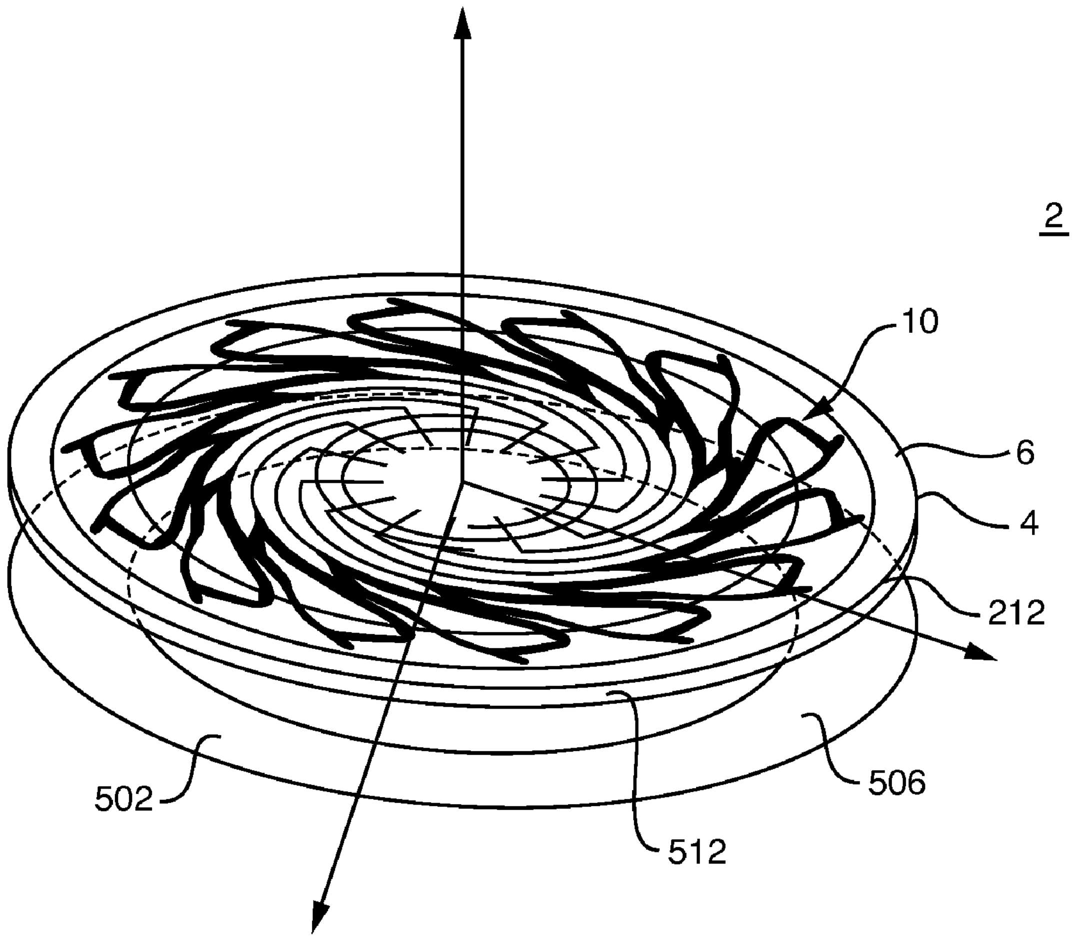


FIG. 5

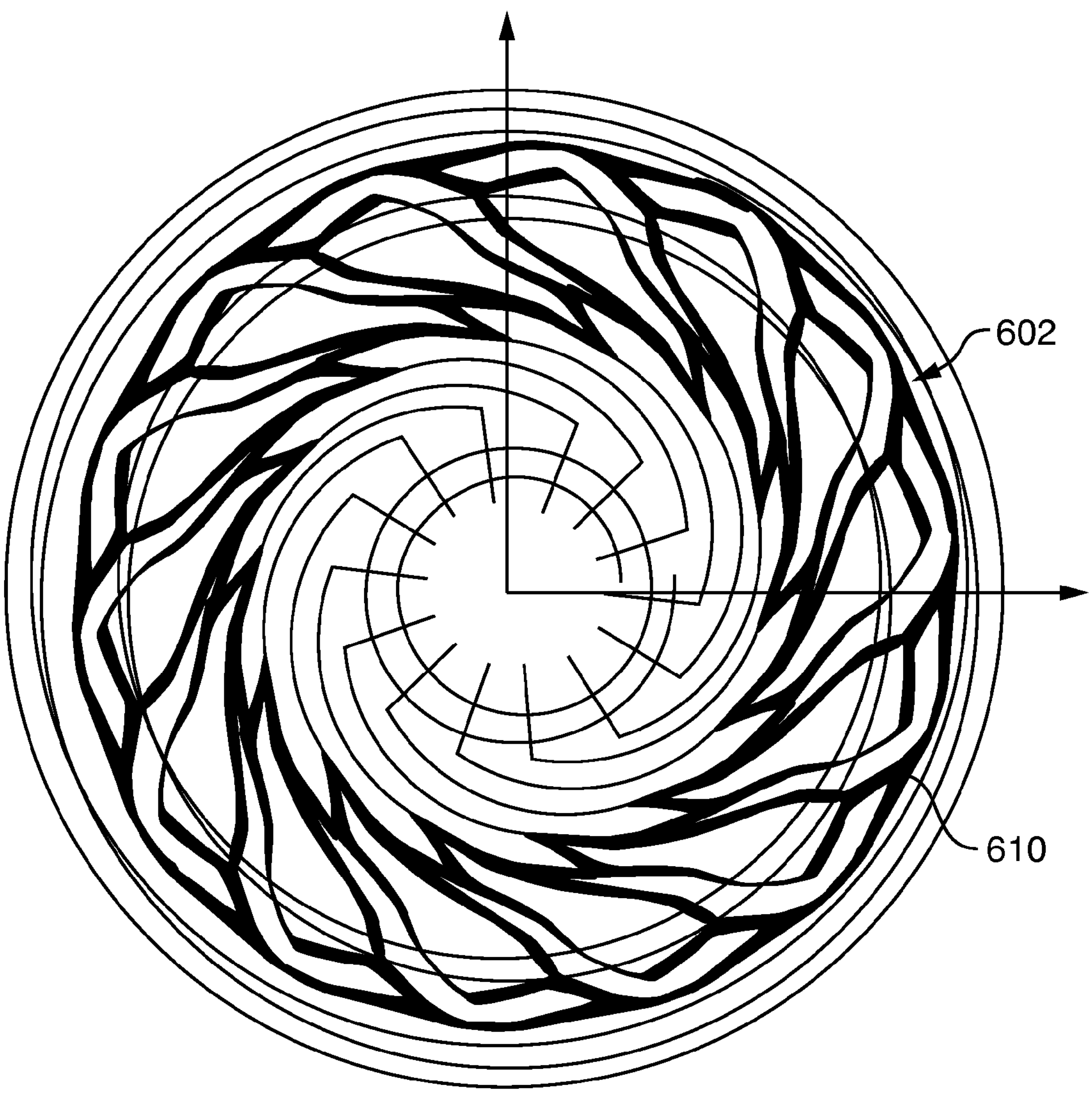


FIG. 6

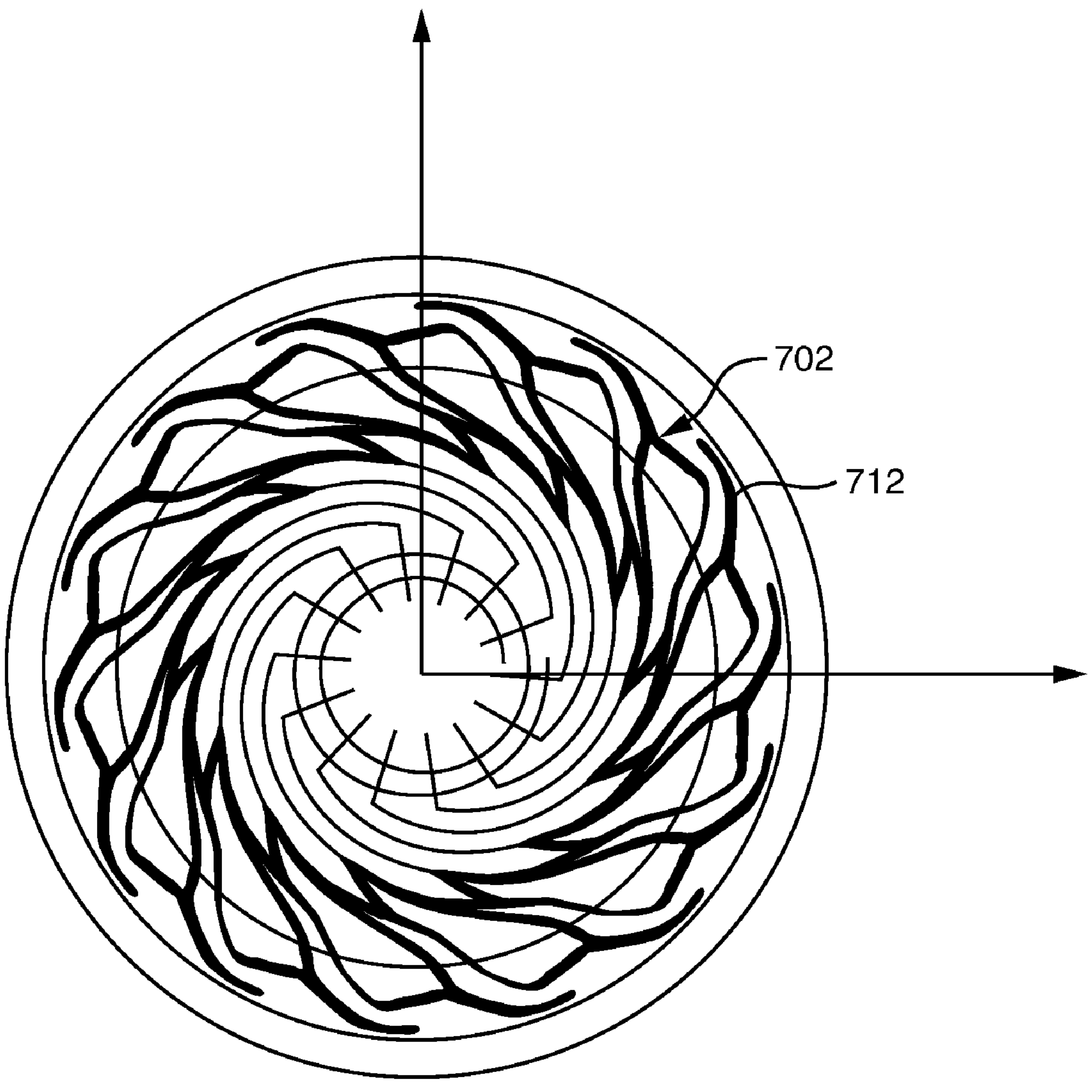
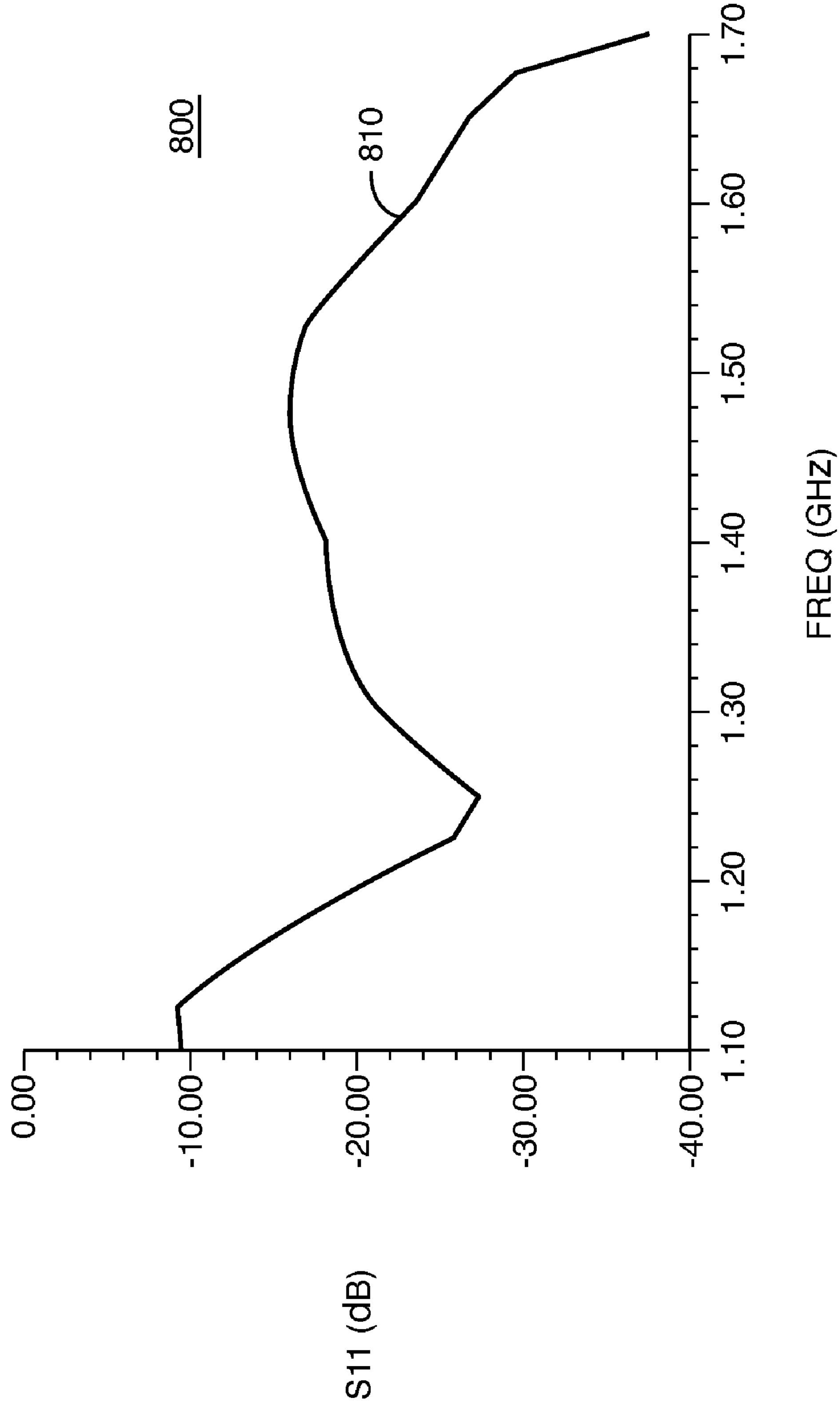


FIG. 7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S11 (dB)
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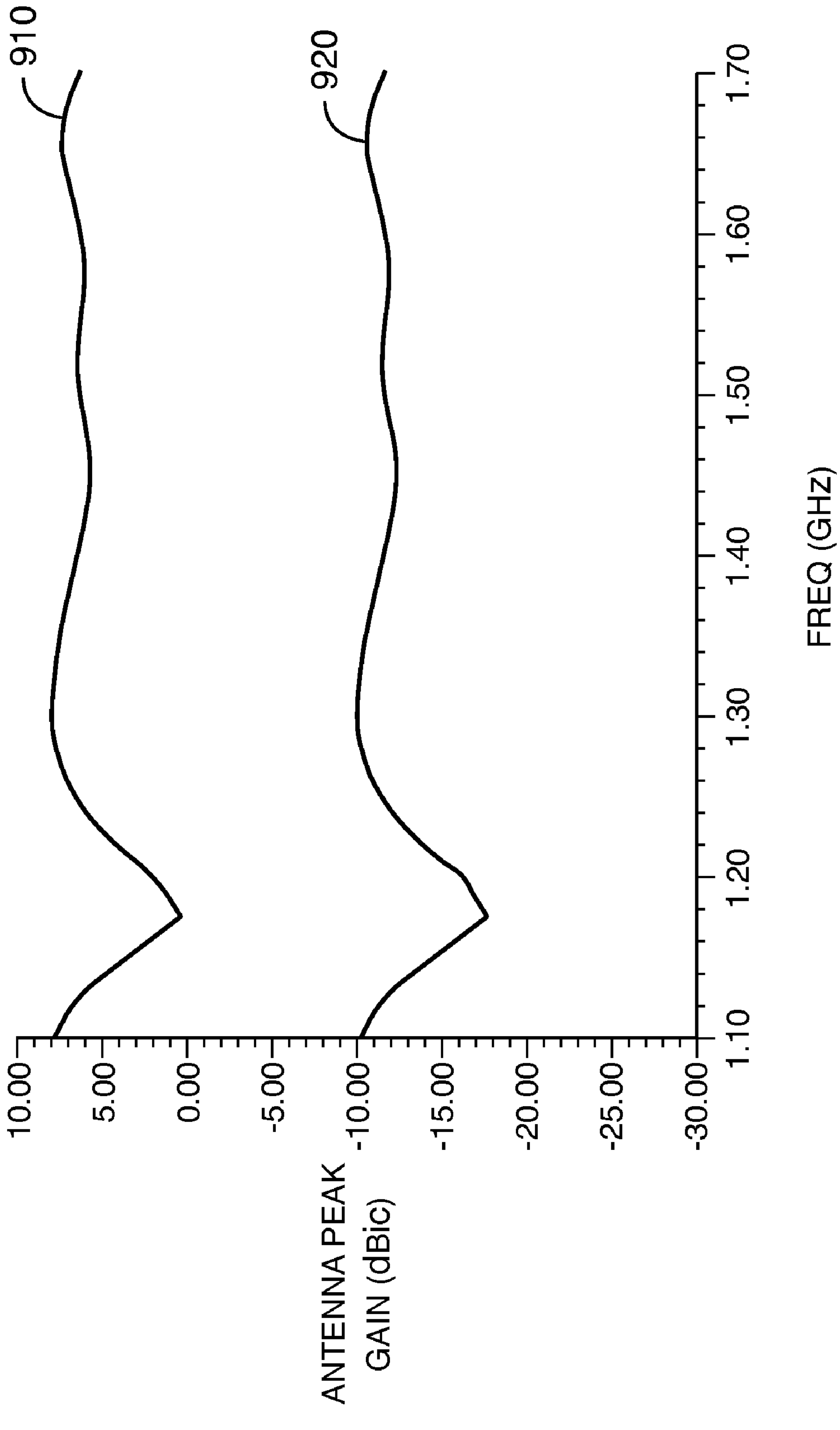
-10.00
-20.00
-30.00
-40.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
FREQ (GHz)

FIG. 8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920
ANTENNA PEAK GAIN (dBic)
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0.00
-5.00
-10.00
-15.00
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1.10
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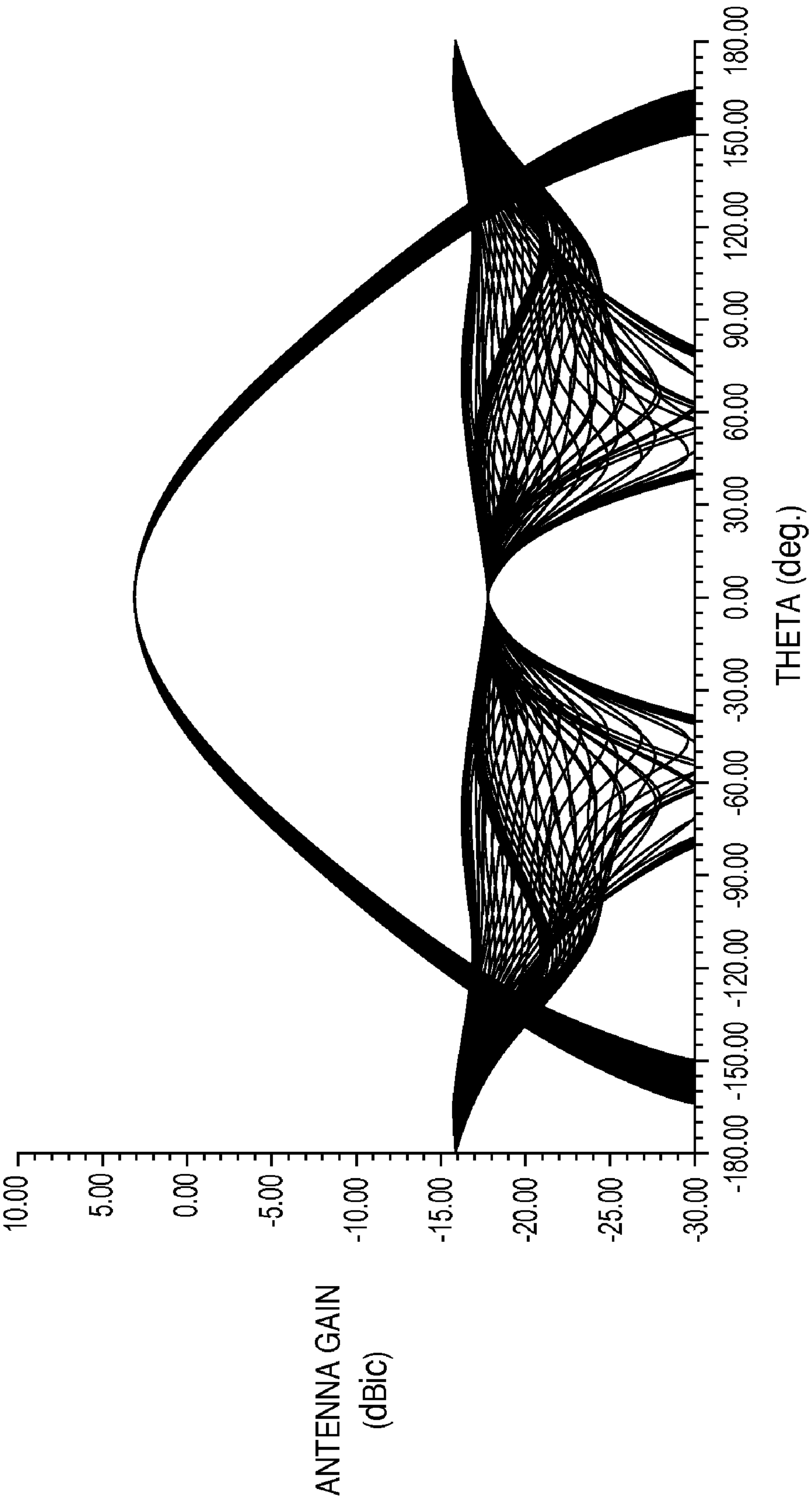
1.30
1.40
1.50
1.60
1.70
FREQ (GHz)

FIG. 9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10.00
5.00
0.00
-5.00
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-15.00
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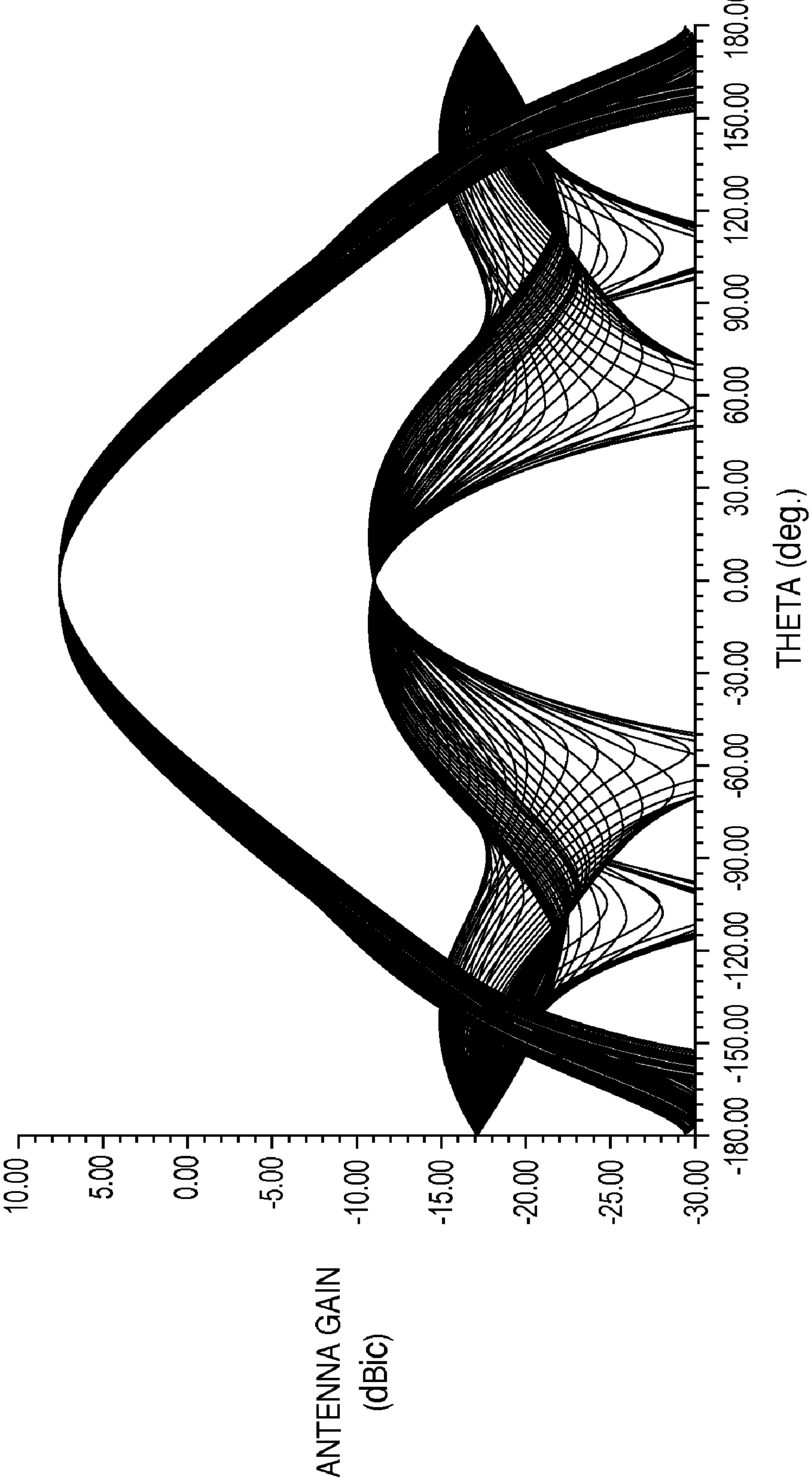
-150.00
-120.00
-90.00
-60.00
-30.00
0.00
30.00
60.00
90.00
120.00
150.00
180.00
THETA (deg.)

FIG. 10A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5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
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-180.00
-150.00
-120.00
-90.00
-60.00
-30.00
0.00
30.00
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90.00
120.00
150.00
180.00
THETA (deg.)

FIG. 10B

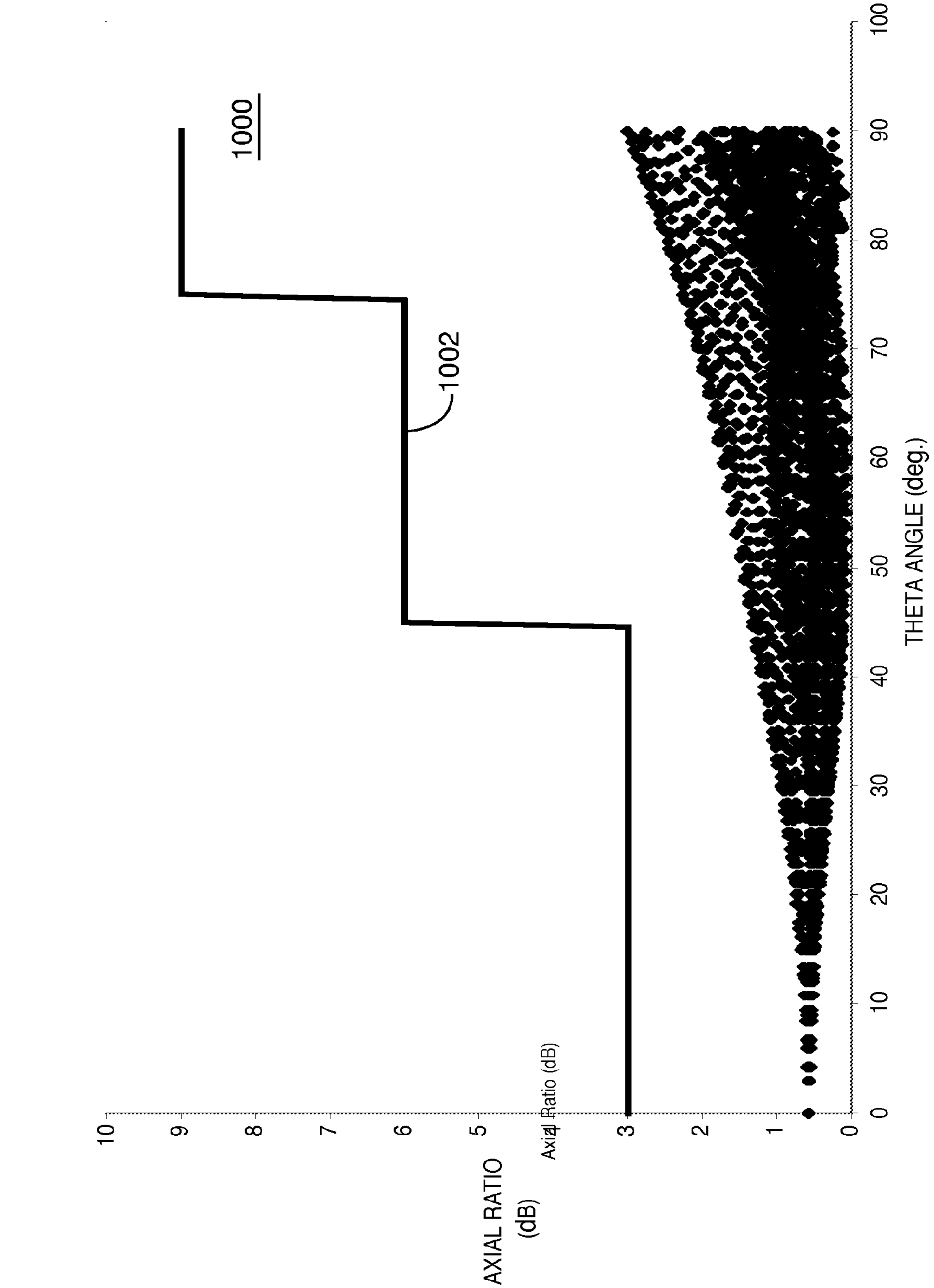
1000
1002
AXIAL RATIO (dB)
Axial Ratio (dB)
0
1
2
3
4
5
6
7
8
9
10
THETA ANGLE (deg.)
0
10
20
30
40
50
60
70
80
90
100

FIG. 11

LEAKY WAVE ANTENNA WITH RADIATING STRUCTURE INCLUDING FRACTAL LOOPS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is related to planar spiral slot antennas and, more particularly, to such antennas having a wide bandwidth.

2. Background Information

Antenna design requirements differ depending upon the particular application of the antenna. Recently, there is a demand for antennas which have the capability of acquiring RF signals from various satellite ranging systems. For example, the satellite ranging systems include the United States Global Positioning System (GPS), the Russian Federation GLONASS System, the European GALILEO System, and commercial services such as the OmniSTAR® System, which provides GPS enhancement data via satellite.

The various satellite ranging systems use signals in different frequency bands, which range from 1175 MHz to 1610 MHz. Thus, a wide bandwidth is required for an antenna designed to receive signals from different ranging systems, and in particular for an antenna designed for use with all of the systems.

There are some known wide bandwidth antennas, however, these antennas tend to have a three dimensional architecture comprised of a stack of individual planar antennas or a complex patch antenna structure. In either case, the three dimensional nature of the design leads to a high profile antenna which is not suitable for aircraft or other applications in which a small form factor is a critical feature or a desirable feature.

In addition to a low profile physical structure, it is highly desirable that a multi-mode ranging application (i.e., GPS, GLONASS, GALILEO, OmniSTAR®-L5,) antenna have a common phase center for the incoming signals at the various frequencies (e.g., from 1175 MHz to 1610 MHz). This is important because the positioning measurements from the various ranging systems are calculated with reference to the phase center of the antenna. Although there are known processes for correcting phase center variation when the geometric phase center of an antenna and the electrical phase center of that antenna are misaligned, any such misalignment must be minimal for high accuracy multimode ranging applications. For example, in many applications, geodetic measurements must be accurate to the millimeter level. However, typically, a common phase center has not been provided even with an error within an acceptable tolerance range by the wide band, three-dimensional antenna structures discussed previously.

A commonly owned U.S. Pat. No. 6,452,560 issued on Sep. 17, 2002, to Kunysz for a SLOT ARRAY ANTENNA WITH REDUCED EDGE DIFFRACTION, which is incorporated herein by reference, describes a low profile slot array antenna in which the geometric and electrical phase centers are aligned. A conductive layer on the front antenna surface includes the array of slotted openings. When an electromagnetic signal is fed into one end of a transmission line and sequentially coupled into the slotted openings, a corresponding signal is emitted from the antenna substantially in the direction of the antenna axis. The front antenna surface also includes a surface wave suppression region enclosing the slotted array and a plurality of through openings disposed between the surface wave suppression region and the peripheral edge of the antenna to reduce defraction of the emitted signal at the peripheral edge. This antenna is particularly useful in the United States Global Positioning System as its slotted openings are tuned to receive both the L1 and L2 frequency bands. However, the antenna was not designed to receive a wider bandwidth including satellite ranging signals from the other systems previously mentioned.

It is also important in antenna design to provide an improved gain at low elevation signals, while still maintaining multi-path rejection. Reduced signal variation is also important in the azimuth plane at low elevation angles for L-band signals in the 1520 to 1560 MHz range.

It is thus an object of the invention to provide an antenna which has a wide bandwidth and a common phase center across the frequency band of interest. Additionally, it is an object of the invention to provide reduced signal variation in the azimuth plane and low gain at low elevation angles, and improved polarization purity.

Other objects of the invention will be apparent from the following detailed description.

SUMMARY OF THE INVENTION

The disadvantages of prior techniques are overcome by the present invention which is a wide bandwidth antenna that acquires RF signals from multiple satellite ranging systems including GPS, GLONASS, GALILEO and related commercial enhancement providers such as OmniSTAR®. The antenna of the present invention is a planar slot array antenna including a multi-arm radiating structure of interconnected slots, where each slot begins as a spiral and flares into a fractal loop configuration. A leaky wave microstrip multiple turn spiral feed network is used to excite the radiating structure of the antenna.

More specifically, the antenna is comprised of a non-conductive substantially planar printed circuit board ("PCB") substrate having an upper surface, which is metallized. The radiating structure is etched into the metallized upper surface of the substrate. As noted, the radiating structure is a network of interconnected slots that are shaped such that they begin as spiral slots and flare at their respective ends into fractal loop configurations. The fractal loop configuration at the end of each slot is coupled to the fractal loop configuration of an adjacent slot. This radiating structure of interconnected apertures create many RF paths, to open the bandwidth for wide bandwidth performance.

The flare of the slot arms also results in increased impedance at the end of the arm. By increasing the impedance at the end of the arm, a previous impedance discontinuity that may have existed is reduced in magnitude, leading to a smoother current distribution across the antenna. This continuously varying slot width and the interconnections between adjacent slot arms further smoothes out amplitude and phase patterns in the azimuth plane of the antenna. The radiating structure also provides a common phase center for the frequency bands of interest.

A microstrip multiple turn spiral transmission line is disposed on a lower surface of the substrate. The spiral shape of the transmission line improves the bandwidth performance of the antenna and improves the antenna efficiency in that the spiral feed microstrip crosses each slot twice thus allowing for the energy from each slot to be collected twice. In accordance with one aspect of the invention, the spiral feed microstrip is a two turn spiral. The spiral shape of the microstrip feeding transmission line has a larger bandwidth compared to circular feeding structures.

A shallow metallic ground plane is disposed adjacent to the lower surface of the substrate, which allows a relatively low profile structure. A second PCB board can be placed between the antenna substrate and the ground plane for additional RF absorption.

The antenna of the present invention may also include a surface wave suppression region which comprises an array of metallized openings along the peripheral edge of the antenna which causes diffraction of surface waves.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention description below refers to the accompanying drawings, of which:

FIG. **1** is a diagrammatical view of the upper surface of an antenna in accordance with the present invention;

FIG. **2** is a cross-sectional view of the antenna of the present invention;

FIG. **3**A is a diagrammatical view of the lower surface of the antenna illustrating the multiturn spiral microstrip feeding structure of the present invention;

FIG. **3**B is a diagrammatical view of the upper surface of the antenna of the present invention also depicting the microstrip feedline coupled with the slot arms of the radiating structure;

FIG. **4** is a simplified schematic view of the top layer of the antenna of FIG. **1** depicting the surface wave suppression region;

FIG. **5** is a side elevation of the antenna of the present invention in which the ground plane is visible;

FIG. **6** is an alternative embodiment of the invention showing an alternative radiating structure;

FIG. **7** is another embodiment of the invention showing yet an alternative radiating structure;

FIG. **8** is a graph of Return Loss for the antenna of the present invention with S11 in decibels on the ordinate versus frequency on the abscissa;

FIG. **9** is a graph of antenna peak gain over frequency for a right hand circularly polarized signal and a left hand circularly polarized signal for the antenna of the present invention;

FIG. **10**A is a simulated radiation pattern for the antenna of the present invention at 1227.6 MHz;

FIG. **10**B is a simulated radiation pattern for the antenna of the present invention at 1575.4 MHz; and

FIG. **11** is a measured axial ratio pattern at 1575.4 MHz for the antenna of the present invention.

DETAILED DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

FIG. **1** is a diagrammatical view of the antenna **2** of the present invention illustrating the substrate **4** which is made of a PCB material. The upper surface **6** of the substrate **4** is metallized or plated. A radiating slot structure **10** is etched into the metallized upper surface **6**, using standard PCB techniques. In accordance with the invention, the radiating slot structure **10** is a multi-armed aperture-coupled network with N spiral slot arms in a self-complementary structure, with each slot arm terminating in a fractal slot geometric shape. This creates a fixed beam phased array of aperture-coupled slots optimized to receive a right hand polarized signal.

More specifically, the radiating slot structure **10** includes a plurality of spiral slot arms **12** through **38**. In the illustrative embodiment of FIG. **1**, there are fourteen spiral slot arms. However, in other applications of the invention, the radiating slot structure may contain a different number of spiral slot arms or may contain apertures having different configurations and/or dimensions, as discussed further herein, while remaining within the scope of the present invention.

The spiral slot arms **12-38** are arrayed about an antenna phase center **50**. Wherein the radiating slot structure is composed of N spiral slot arms, the spatial difference between each two consecutive spiral slot arms, for example, arms **12** and **14**, is preferably $2\pi/N$, where N is the number of spiral slot arms.

The dimensions of the individual slot arms and the interconnections between adjacent arms are determined, in accordance with the invention, by the desired RF frequency band to be received by the antenna. As used herein, the term "frequency band(s) of interest" shall mean one or more of the frequency bands used by the various satellite ranging systems that are to be received by the antenna. These frequency bands include one or more of GPS, GLONASS, GALILEO and related commercial enhancement providers such as OmniSTAR®. If the frequency bands from all such systems are of interest, the overall band ranges from 1175 MHz to 1610 MHz. In addition, there may be other frequencies used outside of that range that can be received using an antenna constructed in accordance with the invention, with appropriate dimensions.

For the purpose of a complete description, a particular embodiment of the invention, with examples of the dimensions of the radiating slot structure **10**, will be provided. It should be understood, however, that the description is provided for illustrative purposes only and is not limiting to the invention.

In the illustrative embodiment of FIG. **1**, the radiating slot structure **10** has 14 spiral arms terminated into fractal loop configurations. In the illustrative embodiment of FIG. **1**, the antenna **2** is intended to receive all of the frequencies of the various satellite ranging systems. These frequencies range from 1175 MHz to 1610 MHz.

More specifically, in this embodiment and application, the dimensions of the radiating slot structure are given with reference to slot **12** of FIG. **1**, and the beginning of the measurement is taken from the beginning of the slot, which point is indicated in FIG. **1** by the arrow labeled "START." The spiral slot arm **12** begins as a flared spiral and then has a fractal loop configuration **60** at its distal end. The point where the fractal loop **60** begins is the same point at which the slot interconnects with the adjacent inner slot **38**, which is designated by reference character **61**. The distance from the start of the slot (START) to reference character **61** is, in accordance with the invention, one half wavelength ($\lambda/2$) of the OmniSTAR® frequency band of interest (which within the L-Band). The distance along the outer edge of the spiral slot arm **12** from the "START" point to where the fractal loop **60** begins, which is the same point slot **12** interconnects with the adjacent outer slot **14**, is designated by reference character **62**. This distance to reference character **62** is one quarter wavelength ($\lambda/4$) of the lowest frequency band of interest in the application, which in this example is L5, E5.

The distance along the spiral slot **12** from the START point to where the slot **12** forks into two arms, separating adjacent fractal loops is designated by reference character **63**, and it is one half wavelength ($\lambda/2$) of the highest frequency band of interest, which in this example is Glonass L1 or "G1". The distance along the spiral slot **12** from the START point to where the left arm of the fork ends, which is called the "boot" herein is designated by reference character **64**, and it is one half wavelength ($\lambda/2$) of the lowest frequency band of interest, which in this application is L5, E5.

The distance along the spiral slot **12** from the START point to where the right arm of the fork ends in the fractal loop **60** is designated by reference character **65**, and this distance **65** is one half wavelength (λ/2) of the second lowest frequency band of interest (L2). The perimeter length around the fractal loop **60** is schematically indicated by the arrow associated with reference character **66**. In the illustrative example, the perimeter **66** is one half wavelength (λ/2) of the mid-frequency of all frequency bands of interest, which in the illustrative embodiment is approximately 1.395 GHz. It is noted that in the illustrative example, the lowest frequency is 1.175 GHz (L5, E5) while the highest is G1 (1.61 GHz).

In accordance with the invention, the spiral slot arms also have a continuously varying width. In the illustrative embodiment, the width of the spiral slot **12** is 0.3 mm in the beginning at the START point, then the slot is continuously flared to about 2 mm at the fork junction (**63**).

As noted, the unique radiating slot structure **10** of the present invention, with its intercoupled apertures and fractal loop geometry opens the radiating bandwidth of the overall antenna **2** by providing multiple and varied RF paths for the incoming signals. Higher order fractal loops can be utilized in the radiating structure design under appropriate circumstances.

FIG. **2** is a cross-sectional view of the antenna **2** of the present invention, in which like components have the same reference characters as in FIG. **1**. The antenna **2** comprises a substrate **4** of a dielectric or other non-conductive PCB material. As noted a metallized a conductive layer **206** is disposed on the upper surface **6** of the substrate **4**. The upper surface **6** is bounded by a peripheral edge **208**. As can be seen in cross section, each of the slotted openings **12**-**18** (the remaining slots are not shown for purposes of clarity of illustration) which slots are described in detail with reference to FIG. **1**, extend from the upper surface **6** to a top aspect **210** of the substrate **4**. The substrate **4** has a lower surface **212**, on which a feeding network, generally designated with reference character **220**, is disposed.

Turning now to FIG. **3**A, the feeding network **220** of the antenna is discussed in greater detail. In accordance with the invention, the feeding network **220** consists of a leaky wave spiral microstrip transmission line **302**. The transmission line **302**, which is disposed on the lower surface **212** of the substrate **4**, is substantially spiral with an input end **304** for receiving electromagnetic signals and a terminal end **305** which may be electrically connected to a load impedance (not shown). The transmission line **302** couples electromagnetic energy between the transmission line **302** and the slotted arms **12**-**38**.

The electrical phase length of the feeding network **220** is set to approximately 2π/N, where N is the number of spiral slot arms in the radiating slot structure of the antenna. The 2π/N approximation of the feed network is achieved by constructing a multi-turn spiral microstrip line **302** beneath the slots, to provide the required progression of the microstrip line electrical phase length between adjacent slots at a wide range of frequencies. A stable phase center and an excellent circular polarization over a wide frequency range are thus achieved using this feeding network **220**. The feeding network **220** also maintains approximately uniform amplitude excitation for all slots.

The interconnection between the feeding network and the radiating slot structure can be understood with reference to FIG. **3**B in which the both slots **12**-**38** as well as the microstrip feed line **302** of the feeding network **220** are shown. It can be seen from FIG. **3**B that the microstrip feed line **302** crosses each slot twice. For example, for the slot **12**, the microstrip feed line crosses the slot **12** at region **306** and again at region **310**. Accordingly, the electromagnetic coupling between the transmission line **302** and the slotted opening **12** occurs in two regions allowing for the information to be collected a second time which gives rise to a more accurate measurement.

Turning to FIG. **4**, the upper surface of an alternative antenna constructed in accordance with the present invention is shown in schematic form with the fourteen spiral slot arms, and a peripheral edge **410** that includes an optional surface wave suppression region **420**, which comprises a photonic band gap (PBG) material disposed within the conductive metallized layer **206**. The surface wave suppression **420** region comprises a plurality of openings **422**-**424** that are spaced such that there are a predetermined number of opening per unit wavelength. The openings are preferably spaced apart by less than ¹⁄₁₀λ to form a solid wall to diffract surface waves. These openings to do not affect the bandwidth of the antenna reception. The surface wave suppression features improve antenna performance particularly when a thick PCB substrate is being used. The larger openings **450** are used for securing or mounting the antenna **2** to the application device.

FIG. **5** is a side elevation illustrating the antenna ground plane. As illustrated in FIG. **5**, the antenna substrate **4** has the radiating slot structure **10** on an upper surface **6** thereof. The substrate **4** is backed by a shallow metallic ground plane **502**, which is placed contiguous to the lower surface **212** of the substrate **4**. A cavity **506** is formed between the ground plane **502** and the lower surface **212**. The depth of the cavity **506** is 15 mm which translates from λ/16 to λ/12 over the frequency band of interest range. This allows a relatively low profile antenna compared to other cavity antenna using a standard λ/4 (quarter wavelength) cavity depth. A 10 mm thick RF foam absorber **512**, which may be an additional PCB layer, can be placed between the substrate **4** and the ground plane **502** to resist leakage of cross-polarized signals from the antenna **2**.

The antenna **2** of the present invention including the ground plane **502** is lightweight in that it weighs approximately 0.45 kilograms (kg) and is small with a diameter of 5.5 inches.

Alternative radiating slot structures are illustrated in FIGS. **6** and **7**. As illustrated in FIG. **6**, the radiating slot structure **602** is comprised of N spiral arms which are terminated in fractal loops that interconnect to form an outer ring **610**.

FIG. **7** illustrates another variant in which the antenna radiating slot structure **702** includes spiral arms terminated in fractal loops, but which have longer tails **712** at the ends thereof.

These alternative embodiments of FIGS. **6** and **7** are used in other applications in which an increased gain at a lower frequency is desired, but this is at the cost of a reduced gain at the higher frequencies. Thus, the design of the radiating slot structure will be selected, depending upon the parameters and specifications needed for the particular application of the invention.

SIMULATION AND TEST RESULTS

The antenna design of the present invention was tested performing detailed electromagnetic simulations using a high frequency structure simulation ("HFSS".) The measured phase center location for various GNSS bands is illustrated in Table 1. Table 1 shows that it is possible to have a single antenna element with phase center variation not exceeding 2 mm with all bands of interest. Therefore, ranging error introduced by the antenna is minimal when using a combination of GPS, GLONASS and GALILEO positioning satellite systems.

TABLE 1

Measured Phase Center Location for various GNSS bands

Constellation & Signal Type	Vertical Phase Center (mm) Max.	Vertical Phase Center (mm) Ave.	Horizontal Phase Center (mm) Max.	Horizontal Phase Center (mm) Ave.
GPS L5/Galileo E5a	1.2	0.7	1.0	0.7
Galileo E5b	1.3	0.8	1.1	0.7
GPS L2	1.5	0.8	1.2	0.8
Glonass L2	1.8	1.2	1.5	1.1
Omnistar L-Band	0.4	−0.1	1.0	0.8
Galileo E1	0.4	0.0	0.9	0.7
GPS L1	0.5	0.0	0.8	0.6
Galileo E2	0.6	0.3	0.8	0.6
Glonass - L1	0.7	0.4	1.2	0.7

The performance of the antenna of the present invention was tested by conducting electromagnetic simulations using HFSS. An excellent performance for antenna return loss is illustrated in FIG. **8** which is a plot **800** of frequency in gigahertz (GHz) on the abscissa against simulated reflection coefficient values (known as "S11") in decibels (dB) on the ordinate. The curve **810** illustrates the return loops over the frequency range of interest.

The antenna peak gain was simulated as illustrated in FIG. **9**. FIG. **9** is a plot of frequency in GHz against antenna peak gain (boresight) in dB/c. The curve **910** illustrates the right hand circularly polarized (RHCP) peak gain for the antenna, and the curve **920** illustrates the left hand circularly polarized (LHCP) peak gain for the antenna.

A vertical radiation pattern is illustrated in FIG. **10**A for a simulation at a frequency of 1227.6 MHz. A vertical radiation pattern for a simulation of the antenna at the frequency of 1575.4 MHz is illustrated in FIG. **10**B. The symmetry of the radiation pattern at each frequency is apparent in each plot.

The antenna of the present invention was also tested by performing anechoic chamber measurements. The anechoic chamber measurements were used to determine the radiation pattern characteristics and phase center variation over all frequency bands of interest. FIG. **11** illustrates the Axial Ratio of the antenna.

The tests and simulations illustrate that the antenna of the present invention has excellent performance in the areas of antenna return loss, gain, Axial Ratio, Front-Back Ratio and amplitude variation in the azimuth plane over the range of frequency bands of interest. The antenna provides a consistent performance over the frequency band of interest.

The antenna of the present invention is advantageous for precise positioning applications. The antenna has multi-frequency performance guaranteeing uniform performance results across all frequency bands. The low profile of the antenna makes it suitable for applications such as vehicle, aircraft, missile, rocket, and many other high impact applications. The stable phase center and uniform phase radiation pattern across all frequencies of interest of the antenna provides for real-time kinematic positioning applications. Axial ratio and front-back ratio provides good performance in high multi-path environments. The antenna is simple to manufacture and can easily meet harsh environmental requirements making it suitable for marine and arctic applications.

What is claimed is:

1. An antenna, suitable for receiving multiple electromagnetic signals in a frequency band of interest, each signal being of its own respective wavelength λ, said antenna comprising:

a non-conductive, substantially planar substrate having an upper surface and a lower surface;

a conductive metallized layer disposed on said upper surface, said conductive metallized layer having a radiating slot structure etched therein, said radiating slot structure including a plurality of interconnected spiral slot arms, each slot arm being terminated in a fractal loop configuration;

a multi-turn spiral transmission line disposed on the lower surface of said substrate; and

a metallized ground plane adjacent to the lower surface of said substrate forming a cavity between the substrate and the ground plane.

2. The antenna as defined in claim **1**, wherein each fractal loop configuration is interconnected with at least one adjacent fractal loop configuration of an adjacent slot arm.

3. The antenna as defined in claim **2** wherein each said fractal loop configuration also includes a tail portion extending beyond said fractal loop configuration towards a peripheral edge of said antenna.

4. The antenna as defined in claim **1** wherein the spatial difference between each two consecutive spiral slot arms is 2π/N where N is the number of spiral slot arms.

5. The antenna as defined in claim **1** wherein each slot arm has an inner edge and an outer edge, with the width of the slot arm being defined as the distance between the inner edge and the outer edge, and wherein each slot arm has a first width at a first end which is nearest an antenna center point, and said width is flared to a larger dimension at the point where its fractal loop configuration begins.

6. The antenna as defined in claim **5**, wherein the distance along an inner edge of each slot arm from the beginning of the slot arm to a point to where the fractal loop configuration begins is about one half wavelength (λ/2) of an OmniSTAR® frequency band of interest in the L-Band.

7. The antenna as defined in claim **5**, wherein the distance along the outer edge of the slot arm from the beginning of the slot arm to where the fractal loop configuration begins is the point at which the slot arm interconnects with an adjacent outer slot.

8. The antenna as defined in claim **7** wherein the distance along the outer edge of the slot arm from the beginning of the slot arm to where the fractal loop configuration begins is about one quarter wavelength (λ/4) of the lowest frequency band of interest.

9. The antenna as defined in claim **5** wherein each slot arm forks into two arms, separating adjacent fractal loops.

10. The antenna as defined in claim **9** wherein the distance along the slot arm from the beginning of the slot arm to where the slot arm forks into two arms, separating adjacent fractal loops, is about one half wavelength (λ/2) of the highest frequency band of interest.

11. The antenna as defined in claim **3** wherein the distance along the slot arm from the beginning of the slot arm to a tail end is about one half wavelength (λ/2) of the lowest frequency band of interest.

12. The antenna as defined in claim **5** wherein the distance along the slot arm from the beginning of the slot arm to where a right arm of a fork in the fractal loop ends, is about one half wavelength (λ/2) of the second lowest frequency band of interest.

13. The antenna as defined in claim **1** wherein the perimeter around the fractal loop configuration is about one half wavelength of the mid-frequency of all frequency bands of interest.

14. The antenna as defined in claim **1** wherein the electrical phase length of the transmission line is set to $2\pi/N$.

15. The antenna as defined in claim **1** wherein the spiral transmission line is a two turn spiral.

16. The antenna as defined in claim **1** having a wide bandwidth ranging from at least about 1175 MHz to 1610 MHz.

17. The antenna as defined in claim **1** wherein the antenna is adapted to receive signals from one or more of the GPS, GLONASS, GALILEO and OmniSTAR® systems.

18. The antenna as defined in claim **1** further comprising an RF absorber disposed between the lower surface of said substrate and the ground plane.

19. The antenna as defined in claim **18** wherein said RF absorber is a circular component substantially comprised of a PCB material.

20. The antenna as defined in claim **1** wherein a peripheral edge of said antenna includes a surface wave suppression region.

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