United States Patent [19]

Bogner et al.

[11] **3,827,055**

[45] **July 30, 1974**

[54] **LENS FED ANTENNA ARRAY SYSTEM**

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[73] Assignee: **RCA Corporation,** New York, N.Y.

[22] Filed: **Apr. 23, 1973**

[21] Appl. No.: **353,423**

[52] **U.S. Cl.** **343/754,** 343/876, 343/854

[51] **Int. Cl.** **H01q 19/06**

[58] **Field of Search** 343/754, 755, 876, 854

[56] **References Cited**

UNITED STATES PATENTS

3,568,207 3/1971 Boyns et al. 343/854

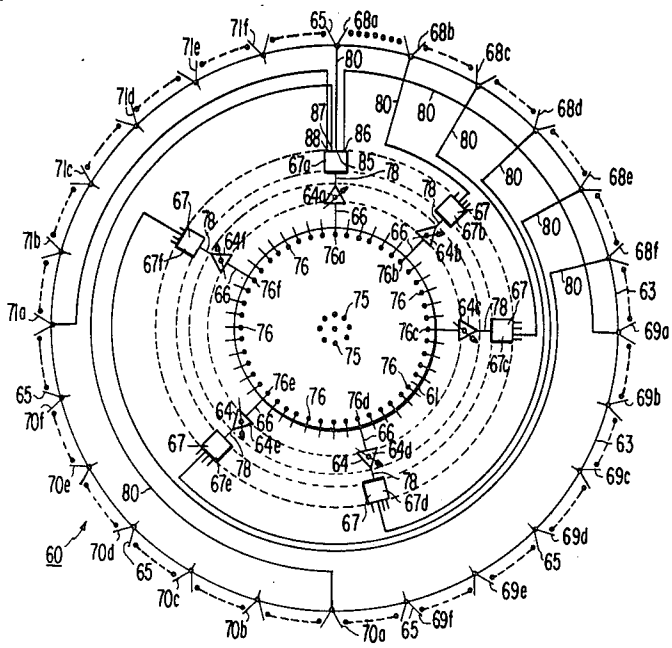
Primary Examiner—Eli Lieberman

Attorney, Agent, or Firm—Edward J. Norton; Robert L. Troike

[57] **ABSTRACT**

A circular phased array system is described which utilizes a lens feed to simplify the problem of commutating the RF distribution system through 360° of steering of the antenna beam. The lens feed consists of a circular parallel-plate radial transmission line with a central set of probes and a ring of peripheral probes. The peripheral probes are coupled via switches to an array of radiating elements arranged in a circle. The central set of probes can be energized and phased to produce electromagnetic energy with an amplitude distribution within the parallel-plate line in any given direction. By selective settings of phase and amplitude of the energy coupled to the central set of probes to achieve the proper energy distribution to the peripheral probes and by operating the switches to determine which radiating elements are coupled to the peripheral probes, a desired directive antenna pattern with low side lobes is provided.

10 Claims, 14 Drawing Figures



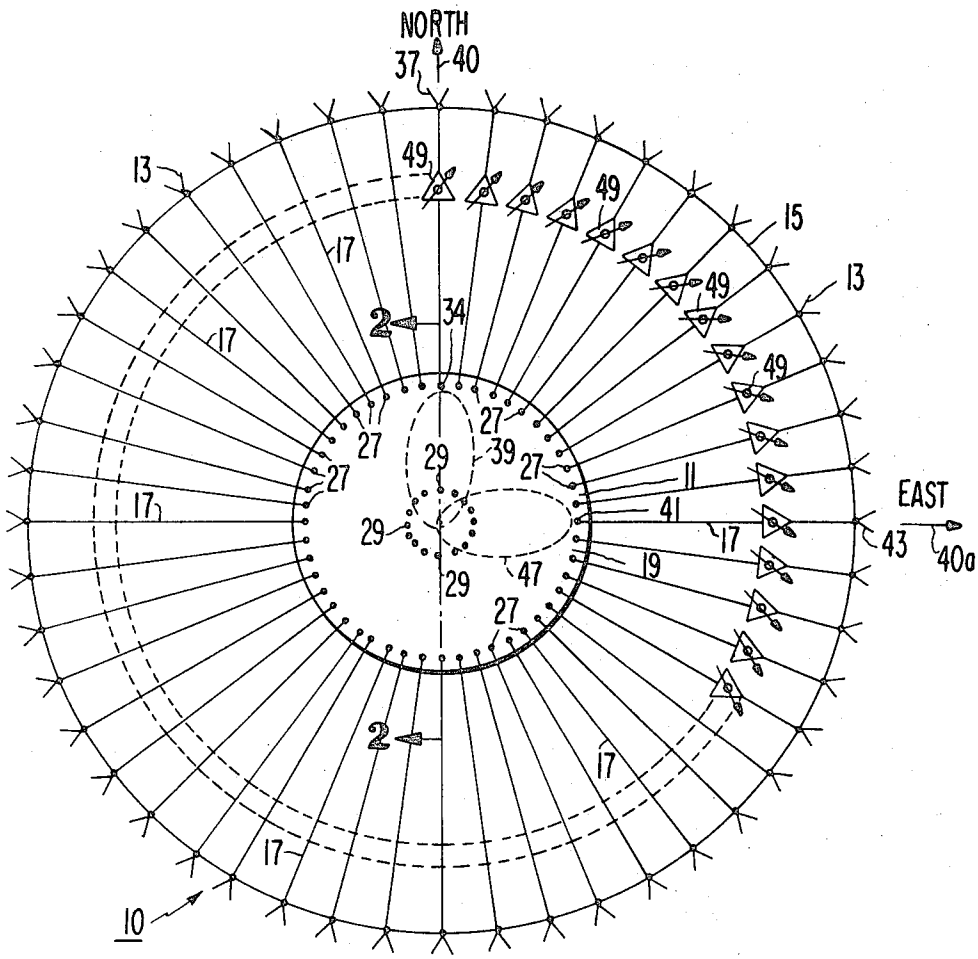

NORTH
37
40
13
49
15
17
2
34
27
29
39
11
41
EAST
43
40a
19
47
10

FIG. 1

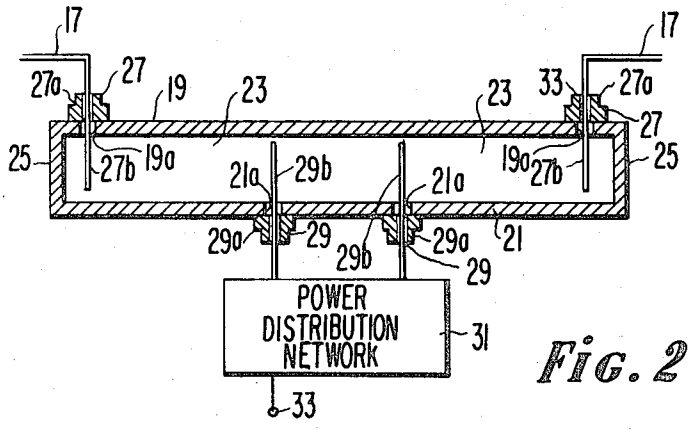

17
27a
27
19
23
33
25
27b
19a
21a
29b
29a
29
21
POWER
DISTRIBUTION
NETWORK
31
33

FIG. 2

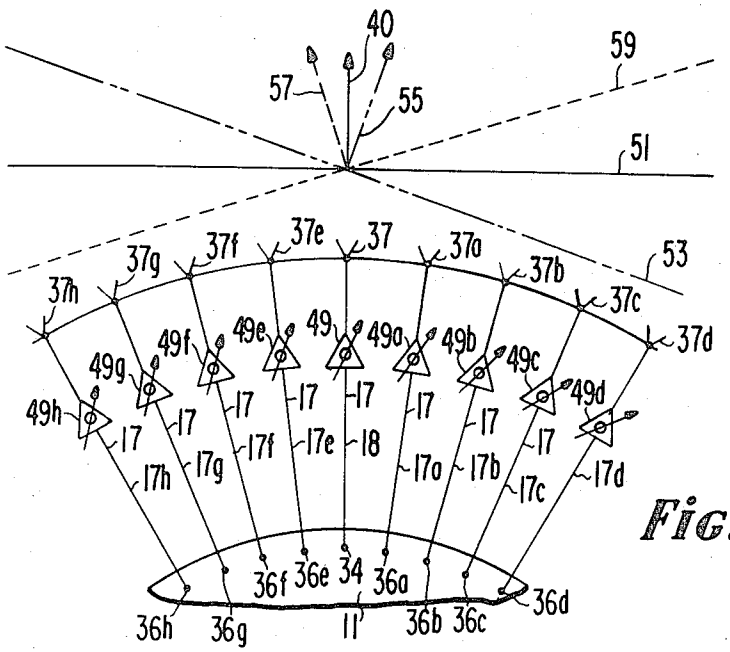

40
57
55
59
51
53
37h
37g
37f
37e
37
37a
37b
37c
37d
49h
49g
49f
49e
49
49a
49b
49c
49d
17
17h
17g
17f
17e
18
17a
17b
17c
17d
36h
36g
11
36f
36e
34
36a
36b
36c
36d

FIG. 3

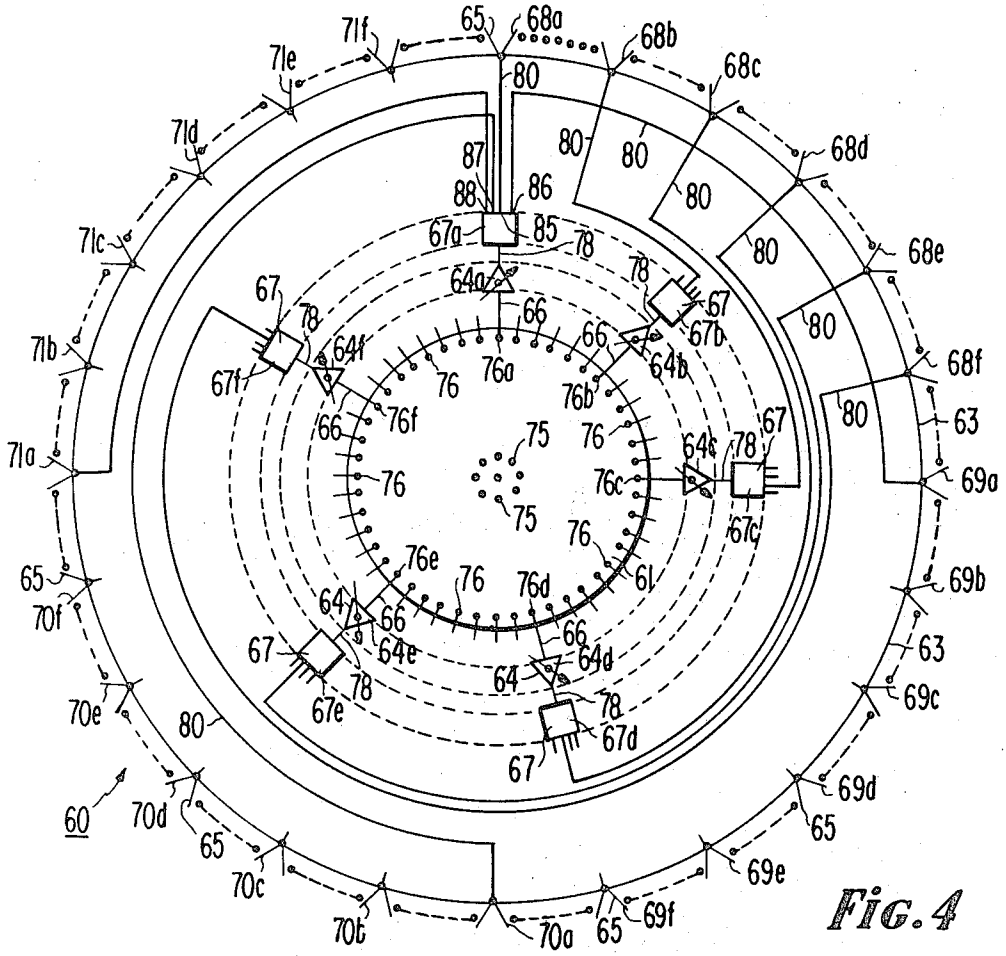

65
68a
68b
68c
68d
68e
68f
63
69a
69b
69c
69d
69e
69f
70a
70b
70c
70d
70e
70f
71a
71b
71c
71d
71e
71f
80
87
88
86
85
78
67
67a
67b
67c
67d
67e
67f
64a
64b
64c
64d
64e
64f
66
76
76a
76b
76c
76d
76e
76f
75
61
60

FIG. 4

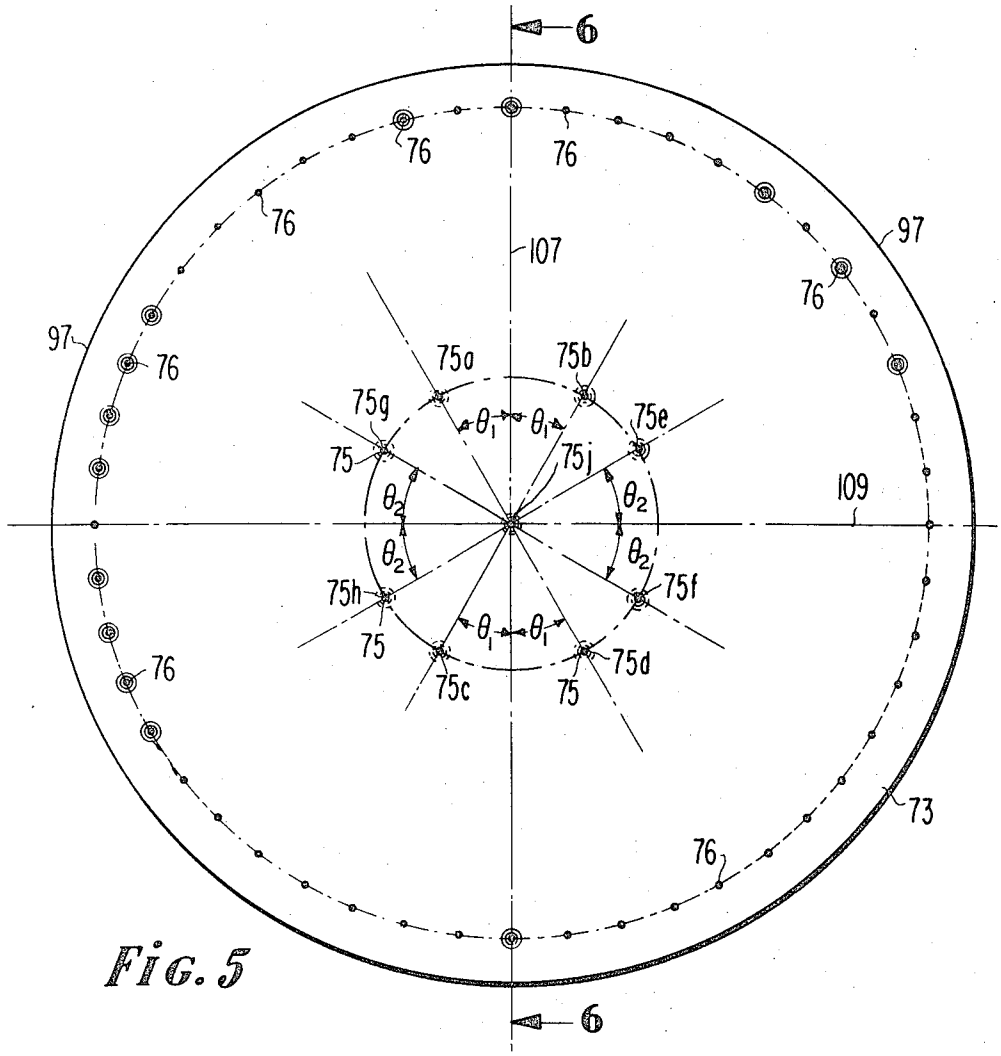


Fig. 5

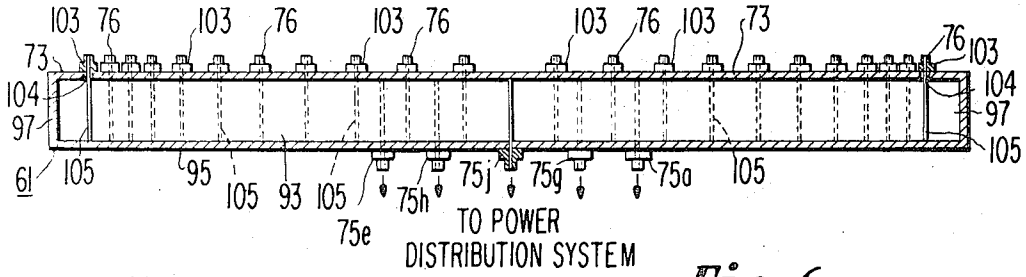


Fig. 6

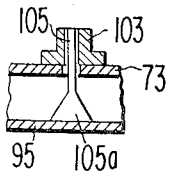


Fig. 7

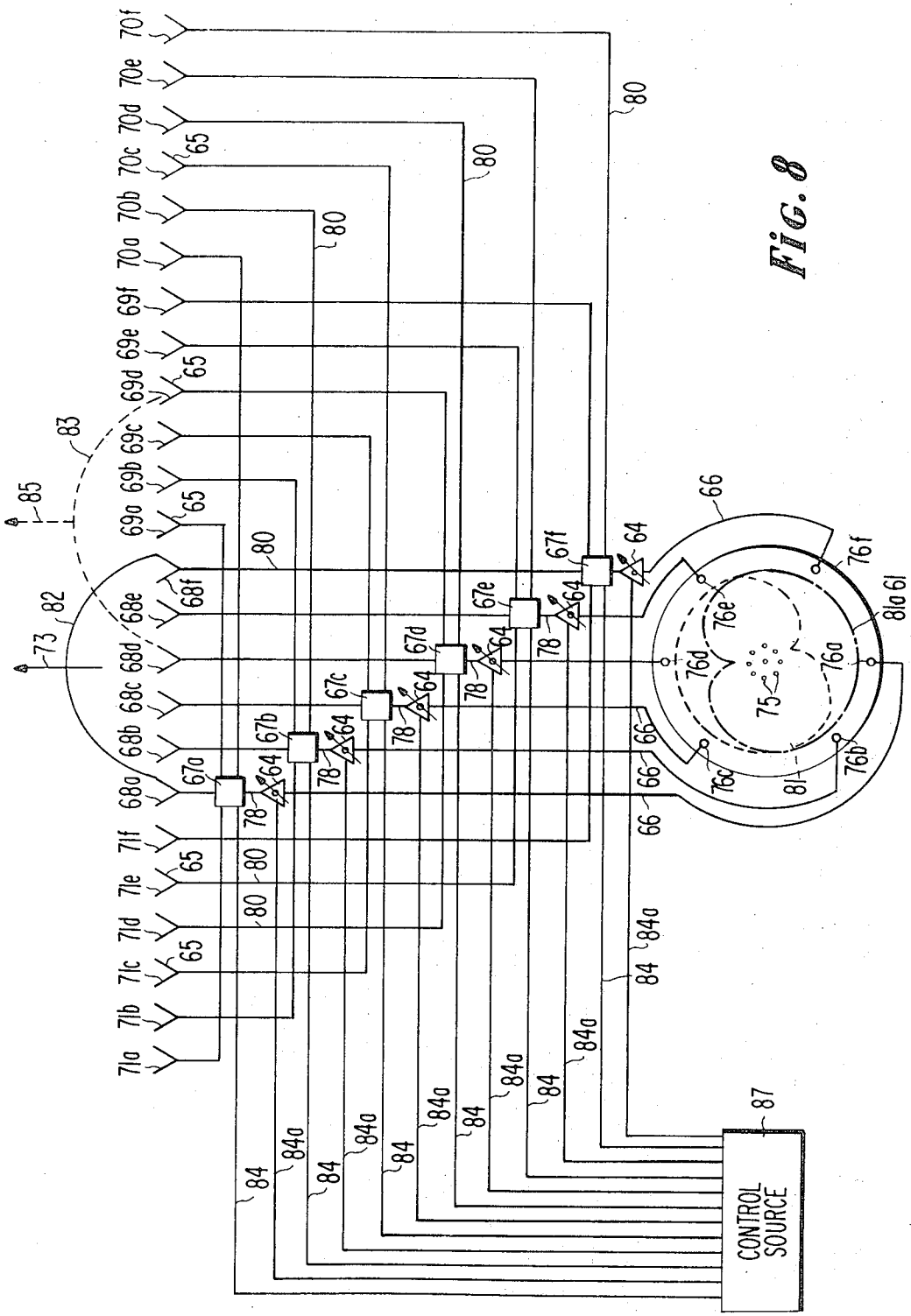

70f
70e
70d
70c
70b
70a
69f
69e
69d
69c
69b
69a
68f
68e
68d
68c
68b
68a
71f
71e
71d
71c
71b
71a
65
80
83
85
82
73
67f
67e
67d
67c
67b
67a
64
78
66
76f
76e
76d
76c
76b
76a
75
81
81a
61
84
84a
87
CONTROL SOURCE

FIG. 8

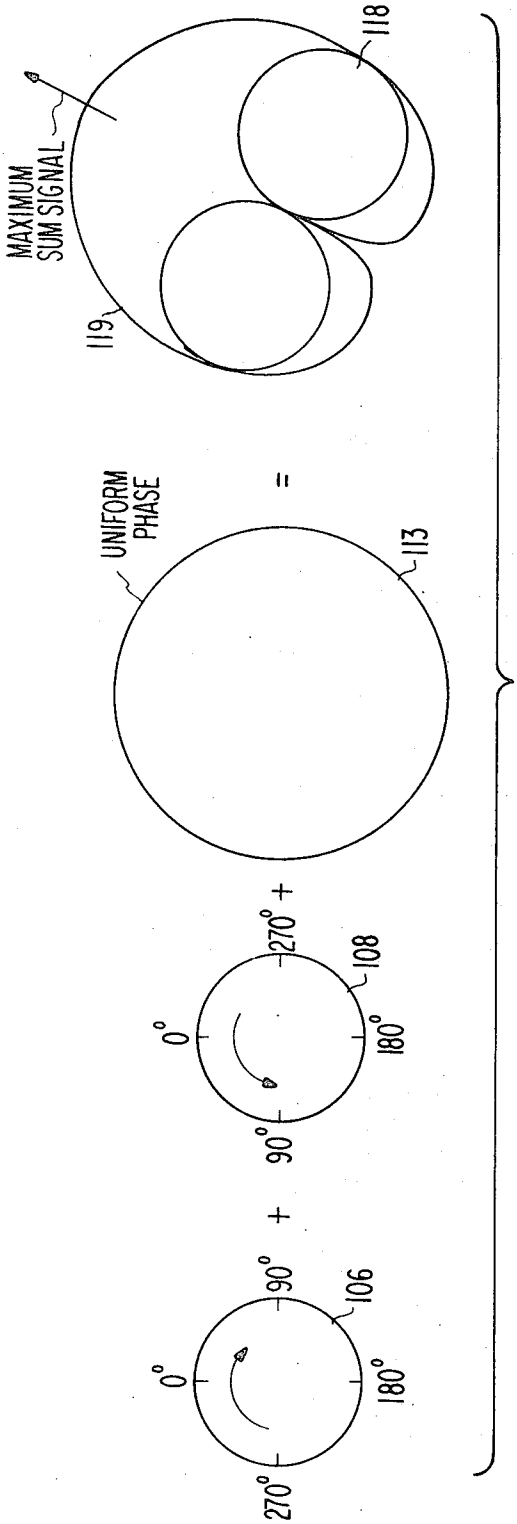


Fig. 9

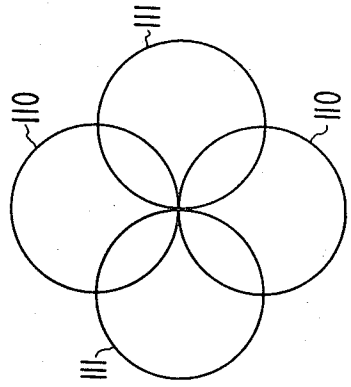


Fig. 13

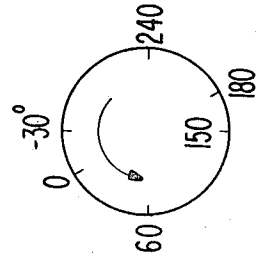


Fig. 11

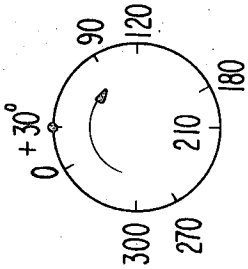


Fig. 10

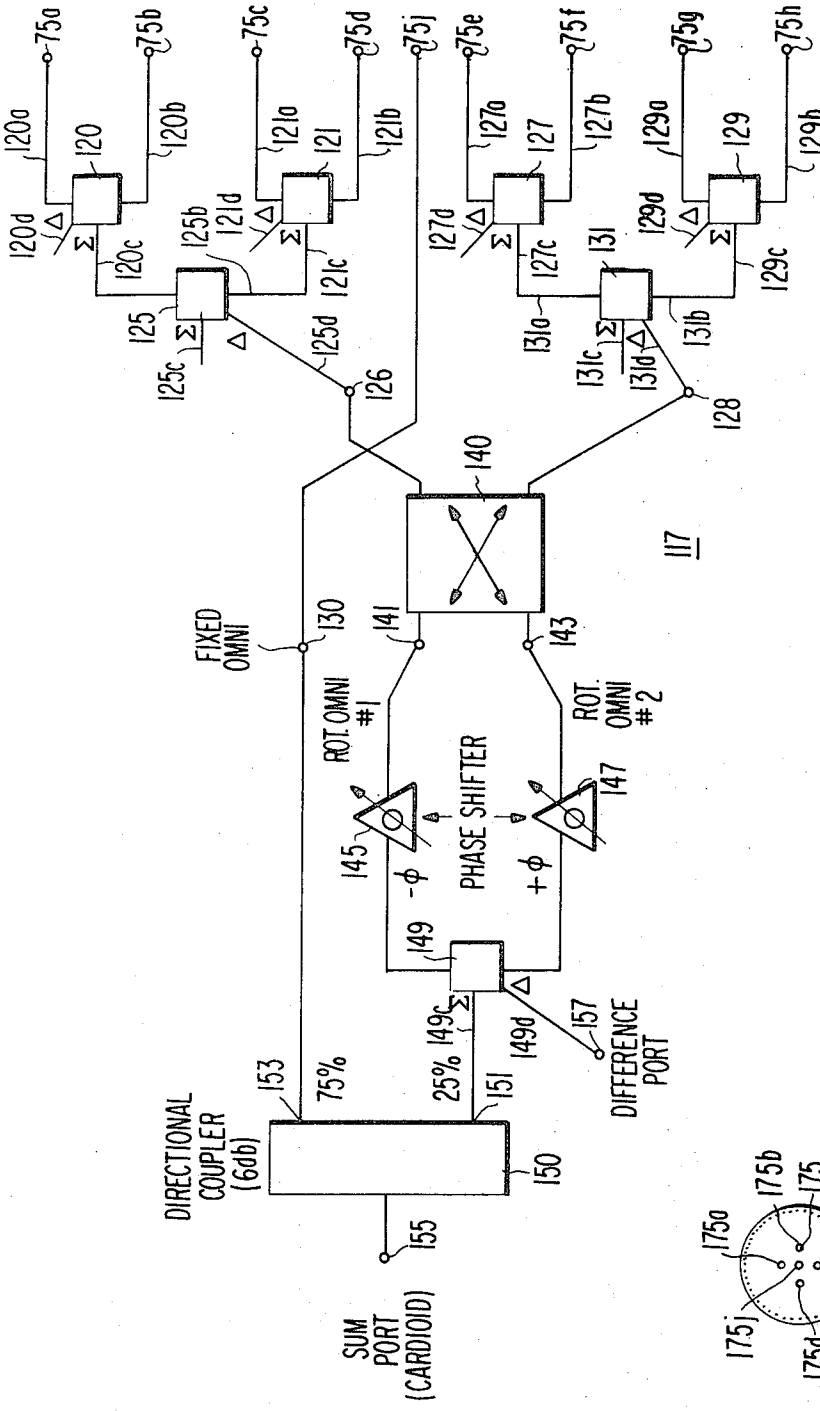

75a
75b
75c
75d
75j
75e
75f
75g
75h
120a
120
120b
120d
120c
121a
121
121b
121d
121c
125b
125
125c
125d
126
127a
127
127b
127d
127c
131
131a
131b
131c
131d
128
129a
129
129b
129d
129c
140
117
FIXED OMNI
130
141
143
ROT. OMNI #1
ROT. OMNI #2
PHASE SHIFTER
145
147
-φ
+φ
149
149c
149d
157
DIFFERENCE PORT
153
75%
25%
151
DIRECTIONAL COUPLER (6db)
150
155
SUM PORT (CARDIOID)

FIG. 12

175a
175b
175
175c
175j
175d
161

FIG. 14

LENS FED ANTENNA ARRAY SYSTEM

BACKGROUND OF THE INVENTION

This invention relates to electronic beam steering antennas and, particularly, to a circular array of many antenna elements with means for beam steering through 360° in fine increments or continuously.

The five most common approaches to provide beam steering through 360° with such an array of antenna elements are briefly described in connection with a typical 192-element circular array, for example. A total of 48 active radiating elements are normally utilized to achieve a directional beam. A first approach is a system that uses a sector-ordering matrix to commutate the amplitude distribution and a set of phase shifters to fine-steer the beam. This first system for this application includes a 1:48 power distribution network, a total of 48 4-bit phase shifters, a 48 × 48 switch matrix with 144 transfer switches and a sector selection network. Beam steering has 11 fine steering phase shifter gradients for the 48 phase shifters and 48 sector ordering commands for the 144 switches. This system requires many diodes for the phase shifters and for transfer switching. High isolation per switch (>40 db) is also a requirement. For a more detailed description of this type of system see "An Electronically-Scanned Cylindrical Array Based on a Switching-and-Phasing Technique" by Richard J. Giannini, in the symposium record of the December, 1969 IEEE G-AP (Antennas and Propagation Group) International Symposium, Austin, Tex.

A second approach is to employ a $N \times N$ Butler beam forming matrix to excite an array of N elements or for the 192 element array a 192 × 192 matrix. This network must employ N or 192 phase shifters for beam commutation. A proposed diode count for such a system would be about 1,536. A more detailed description of this arrangement may be had with reference to a paper entitled "A Matrix Fed Circular Array for Continuous Scanning," by B. Sheleg, in the symposium record of the September, 1968 IEEE G-AP (Antennas and Propagation Group), International Symposium.

A third approach referred to as the sector beam forming technique may be provided for beam steering using a 48 × 48 Butler beam forming matrix which is used in conjunction with 48 phase shifters to index the amplitude and phase of a fixed feed network along the parts of a circular array, and a sector-selection network. A more detailed description of this may be had with reference to the article "An Electronically Scanned Cylindrical Array Switched in Aximuth and Frequency Scanned in Elevation," by B. Sheleg and B. D. Wright, in Proceedings of the Conformal Array Antenna Conference, NELC, San Diego, Calif., January, 1970. This 48 × 48 Butler matrix has many disadvantages. Although the amplitude and phase distribution can be commutated together, any phase error or circuit error affects both parameters. In the example, critical cancellations through six layers of directional couplers and five layers of fixed phase shifters are required to produce the output amplitude and phase distributions. All beams generated within a sector are unique, resulting in for example 500 separate phase ramps required for 500 beam positions per quadrant. This system has relatively large insertion losses because the signal must travel in the above example through six couplers, five

fixed phase shifters, long equalization lines, and through several crossover networks. For a further discussion of the diadvantages of the sector beam forming technique, see the article entitled "Effects of Random Errors on the Performance of a Linear Butler Array," by M. J. Kiss, in IRE Transactions (Antennas and Propagation Group), November, 1962.

A fourth technique referred to generally as the "vector-transfer" technique, for the above example, uses forty-eight (48) 4-bit phase shifters, a 1:48 power divider, forty-eight (48) 4-bit attenuators and forty-eight (48) single pole four throw switches (SP4T) in a sector selection network. This technique requires generally more diodes and has considerably higher loss than the other approaches. For a more complete description of this technique, see the article, "Step-Scanned Circular-Array Antenna," by J. E. Boyns, C. W. Gorham, A. D. Munger, J. H. Provencher, J. Reindel and B. I. Small in Proceedings of the Conformal Array Antenna Conference, NELC, San Diego, Calif., January, 1970.

A fifth possible technique for a ring array is the R-2R lens technique as described in the article, "A Broadband Optical Feed for Circular Arrays," by J. M. Devan, J. E. Boyns and A. D. Munger in the Proceeding of the Conformal Array Antenna Conference, NELC, San Diego, Calif., January, 1970. This system requires that the angle of the feed system of a parallel plate lens by exactly twice that of the array. This would require a large diameter (or heavily loaded) lens. Moreover, it would have a very large switching matrix.

A new antenna array system is described herein which includes a parallel plate lens feed assembly. The basic array system including the parallel plate lens feed assembly is the subject of application Ser. No. 353,421 filed on the even date herewith. The basic system is exemplified by the arrangements shown in FIGS. **1** thru **3.** This arrangement may require many inner probes to achieve the required highly directional pattern within the lens feed assembly. It is also desirable to further reduce the possibility of side and back lobes.

SUMMARY OF THE INVENTION

Briefly, a phased array antenna system is described which includes a parallel plate lens feed assembly with a first plurality of probes arranged in a ring at the periphery of the plates and a second plurality of central probes. A plurality of radiating elements is arranged in a ring-like pattern with N times as many elements as there are probes in the first plurality of probes. A plurality of N-way switches are provided with a different N-way switch coupled to each probe of said first plurality of probes. Each of these N-way switches are coupled to N radiating elements which elements are distributed uniformly about the array. Control of the direction of the radiated beam is had by controlling the power distribution and phase of the signals to the central probes to achieve an energy distribution to the peripheral probes and by controlling the position of the N-way switches to control which antenna elements are coupled to the peripheral probes.

DETAILED DESCRIPTION

A more detailed description follows in conjunction with the following drawings in which:

FIG. **1** is a sketch of a 360° electronically scanned phased array according to one embodiment of the present invention.

FIG. 2 is a sketch of the feed system in FIG. 1 showing a cross-section of the parallel plate radial transmission line lens feed assembly of FIG. 1 taken along line 2—2 with the power distribution network coupled thereto.

FIG. 3 is an illustrative sketch of the fine steering portion of the array shown in FIG. 1.

FIG. 4 is a sketch of an antenna feed system in accordance with a second embodiment of the present invention.

FIG. 5 is a plan view of the radial waveguide lens feed assembly according to the second embodiment of the present invention.

FIG. 6 is a cross-sectional view of the radial parallel plate feed assembly of FIG. 5 taken along lines 6—6'.

FIG. 7 is a partial cross sectional view of the parallel plate line feed assembly illustrating the probes with the center conductor having a conical taper in accordance with one embodiment of the present invention.

FIG. 8 is a sketch illustrating the coarse steering arrangement according to the second embodiment of the present invention.

FIG. 9 is a sketch of azimuth patterns illustrating how the rotatable cardioid pattern is derived.

FIG. 10 is a sketch of an azimuth pattern of a rotating phase omnidirectional pattern that is phase shifted an extra +30°.

FIG. 11 is a sketch of an azimuth pattern of a rotating phase omnidirectional pattern that is phase shifted a (minus) −30°.

FIG. 12 illustrates the power distribution feed network of the second embodiment of the present invention.

FIG. 13 is a sketch of an azimuth pattern of two orthogonal figure-eight patterns.

FIG. 14 is a plan view of a radial waveguide lens feed assembly according to a third embodiment of the present invention.

Referring to FIG. 1, there is illustrated a 48-element phased array antenna system 10 with 360° scan. The antenna array system 10 includes a cylindrical array support structure 15, a lens feed assembly 11, 48 radiating elements 13 and 48 feed lines 17. The lens feed assembly 11 is located coaxially within the cylindrical support structure 15 for the radiating elements 13. The 48 peripherally mounted radiating elements 13 are equally spaced about the array structure 15 and they extend in radial fashion from the center of the cylindrical structure 15. The 48 feed lines 17 are coupled between 48 outer probes 27 associated with the parallel-plate transmission line lens feed assembly 11 and the radiating elements 13. The radial parallel plate transmission line lens feed assembly 11, as shown in FIGS. 1 and 2, includes a pair of parallel overlapping conductive circular plates or disks 19 and 21 with a dielectric medium 23 therebetween so as to form a transmission line. The circular plates or disks 19 and 21 are of the same diameter and totally overlap each other. The plates or disks are spaced less than a half wavelength apart so only the TEM and TE_{NO} modes can propagate where N is any whole number. The edge of the disks 19 and 21 are connected to each other by a conductive band or rim 25 of conductive material to make the parallel plate lens feed assembly 11 a completely enclosed structure confining the propagated energy therein. Near the periphery of the parallel disks 19 and 21 are coupled the 48 outer probes 27 which are equally spaced from each other and are arranged in a circular pattern. Each of these outer probes 27 are coaxial probes with the outer conductor 27*a* (as shown in FIG. 2) coupled to the top plate 19 and with the inner conductor 27*b* being insulated from outer conductor 27*a* and extending in a coupling manner into the dielectric medium 23 located between plates 19 and 21 through a small aperture 19*a* in plate 19.

A second plurality of coaxial probes 29 (represented by dots in FIG. 1), sixteen (16) in number, for example, are arranged in an inner grouping or set near the center of the lens feed assembly 11. Each of the central set of probes 29 have an outer conductor 29*a* and an inner conductor 29*b* with the outer conductor 29*a* coupled to plate 21 and with the inner conductor 29*b* extending in a coupling manner into the dielectric medium 23 through an aperture 21*a* in plate 21. The inner probes 29 are coupled to a power distribution network 31. This power distribution network 31 in response to electromagnetic signal waves coupled to terminal 33, for example, provides energy with selected relative power levels and selected relative phases to the 16 inner or central set of probes 29. These relative power levels and phases are selected to cause a resultant radiation pattern of a certain energy distribution to be emanated towards the outer probes 27 from the central grouping or set of probes 29. This radiation pattern excites electromagnetic energy wave energy at the peripheral probes 27 according to the certain energy distribution. In the example shown in FIG. 1, a directional radiation pattern, indicated by dashed line 39, is excited whereupon the peripheral probes 27 are excited with the particular outer probe 34 receiving maximum power and the outer probes 27 extending on either side of probe 34 having symmetrically decreasing powers. The radiated pattern 39 is made sufficiently narrow, for example, so that the signal energy at those peripheral probes 27 beyond 45° on either side of probe 34 is considered negligible.

As stated previously, the peripheral probes 27 are coupled by the separate transmission lines 17 to the separate radiating elements 13 located about the array structure 15. Since the signal energy at probe 34 is maximum, maximum power is radiated out of the North-pointing radiating element 37 coupled thereto. Symmetrically decreasing power is radiated from the adjacent radiating elements 13 on either side of element 37. The resultant relatively narrow radiation pattern from the array system 10 corresponds with that within the parallel plate transmission line assembly 11 with maximum strength of the beam pointing in the generally North-pointing direction of arrow 40. No appreciable radiation occurs beyond 45° on either side of the arrow 40. The resulting pattern distribution is similar to that of dashed lines 39.

The radiated beam from the elements 13 is commutated by adjusting the relative power level and phase of the signals at the inner probes 29 via adjustments within the power distribution network 31. For example, if it is desired to radiate the relatively narrow beam with maximum strength in the pointing EAST direction of arrow 40*a*, the power distribution of energy coupled to undivided probes of the central probes 29 and the relative phase of that energy at the undivided probes of the central set of probes 29 is selected at the power distribution network 31 so that the pattern within assem-

bly **11** resemble pattern **47** (shown in dashed lines) in FIG. **1.** In this arrangement, maximum radiation occurs at the particular outer probe **41** of probes **27.** Probe **41** is coupled via a transmission line **17** to the EAST pointing radiating element **43.** No appreciable radiation occurs, in the example, beyond about ±45° on either side of element **43** and therefore maximum radiation occurs in generally the EAST pointing direction. By adjusting the power ratio between the central probes **29** and the phase of the signals at the central probes **29,** any selected direction of radiation within 7.5° (360/48) may be achieved. In order to collimate and/or to achieve a continuous scan or steering of the beam within finer increments, a controlled variable phase shifter **49** is coupled in each of the leads **17** between the radiating elements **13** and the probes **27.**

Referring to FIG. **3,** there is illustrated the manner in which the 48 variable phase shifters **49** provide beam collimation and fine beam steering within an arc of plus (+) and minus (−) 3.75°. With the radiated pattern as illustrated by dashed lines **39** in FIG. **1,** the probe **34** of probes **27** is excited with maximum power and with the power at the adjacent probes descending in a symmetrical manner from either side of the probe **34.** Maximum radiation under these conditions is in the general direction of North-pointing direction arrow **40.**

To the right of the particular outer probe **34** in FIG. **3** are the four particular adjacent outer probes **36***a*, **36***b*, **36***c* and **36***d*. To the left of the particular outer probe **34** are the four particular adjacent outer probes **36***e*, **36***f*, **36***g* and **36***h*. Outer probe **34** is coupled via phase shifter **49** and a particular one **18** of the transmission lines **17** to radiating element **37.** Outer probe **36***a* is coupled via phase shifter **49***a* and transmission line **17***a* to radiating element **37***a*. Similarly, probe **36***b* is coupled to radiating element **37***b* via line **17***b* and phase shifter **49***b*. Probe **36***c* is coupled to radiating element **37***c* via line **17***c* and phase shifter **49***c*. Probe **36***d* is coupled via line **17***d* and phase shifter **49***d* to radiating element **37***d*. To the left of North-pointing element **37** are antenna elements **37***e*, **37***f*, **37***g* and **37***h*. Probe **36***e* is coupled via line **17***e* and phase shifter **49***e* to radiating element **37***e*. Probe **36***f* is coupled via line **17***f* and phase shifter **49***f* to radiating element **37***f*. Probe **37***g* is coupled via line **17***g* and phase shifter **49***g* to radiating element **37***g*. Probe **36***h* is coupled via line **17***h* and phase shifter **49***h* to radiating element **37***h*.

When the phase shifters **49** and **49***a* through **49***h* are adjusted to center the beam in the centered direction of arrow **40** in FIG. **3,** the wavefront is along line **51.** The phase shifter **49** and phase shifters **49***a* through **49***h* are adjusted so that the wave from element **37** is delayed relative to the waves from the adjacent radiating elements **49***a* through **49***h* and so that the waves from the radiating elements **49***a* through **49***h* on either side of radiating element **37** are delayed in decreasing amounts from element to element to the right and left of the center element **37.** In other words, phase shifter **49** provides maximum delay, phase shifter **49***a* provides less delay, phase shifter **49***b* provides less delay than phase shifter **49***a*, phase shifter **49***c* provides less delay than phase shifter **49***b*, and phase shifter **49***d* provides less delay than phase shifter **49***c*. Phase shifters **49***a* and **49***e* provide equal delay, phase shifters **49***b* and **49***f* provide equal delay, phase shifters **49***c* and **49***g* provide equal delay, and phase shifters **49***d* and **49***h* provide equal delay. The wavefront can be adjusted to be along dashed line **53** by adjusting phase shifters **49** and **49***a* through **49***h* such that each of the phase shifters **49** and **49***a* through **49***h* provide a relative delay to the corresponding waves that steadily increases to the right. The corresponding radiated beam thereby changes to the direction of arrow **55.** This directional change may be in the above example at +3.75°. The main beam may be rotated −3.75° in the direction of arrow **57** by reciprocally adjusting the position of the phase shifters **49** and **49***a* through **49***h* so that the relative delay to the corresponding wave steadily increases to the left thereby providing a waveform along dashed line **59.**

The power distribution network **31** and the spacing and arrangement of the central set of probes **29** can be made in accordance with the teachings of C. O. Clasen, J. B. Rankin and O. M. Woodward, Jr. in an article entitled, "A Radial-Waveguide Antenna and Multiple Amplifier System for Electronic Scanning," RCA Review, September, 1961, pp. 543 thru 554.

A power distribution network with a central probe or monopole, a next ring or four probes, a next ring of eight probes, a next ring of 12 probes and a final ring of 16 probes to achieve a single narrow beam in a desired direction is described in U.S. Pat. No. 3,090,956 of O. M. Woodward, Jr.

The above-described arrangements require many central probes, such as **16** and **29** in the above examples, to achieve the required highly directional pattern within the lens feed assembly. Also, the above arrangements may have difficulty in reducing side and back lobes to a sufficiently low level.

FIG. **4** illustrates a 192-element array system **60** requiring a less directional pattern within the parallel plate line lens feed assembly and having no significant back lobes and fewer significant side lobes. Referring to FIG. **4,** the array system **60** includes a radial parallel plate line lens feed assembly **61,** an outer circular array structure **63, 192** radiating elements **65,** transmission lines **66, 78** and **80, 48** phase shifters **64** and **48** single pole four-way (SP4T) switches **67.** For purposes of illustration, however, only **24**—radiating elements **68***a* thru **68***f*, **69***a* thru **69***f*, **70***a* thru **70***f* and **71***a* thru **71***f* — of the 192 radiating elements **65** are drawn. There are seven radiating elements **65** —represented by dots and dashes between dots — between each of the particular radiating elements **65** drawn. Also, for purposes of illustration, only a few of the transmission lines **66, 78** and **80,** four-way switches **67** and phase shifters **64** are illustrated, therebeing the number of phase shifters (**48**) and four-way switches (**48**) as indicated previously.

The parallel plate line lens feed assembly **61** is similar to the lens feed assembly **11** in FIG. **1.** Referring to FIGS. **5** and **6** illustrating a plan view and cross-sectional view respectively of lens assembly **61,** the assembly **61** includes a metal disk-shaped enclosure having a top wall **73** and a bottom wall **95** with a rim **97** therebetween. There is a central set of nine probes **75***j*, **75***a* through **75***h* and an outer circle of 48 outer probes **76.** The assembly **61** differs from assembly **11** in that only nine probes are used to make up the central set of probes with one of the nine probes being at the center of the lens feed assembly and the surrounding set of eight probes being arranged in a single concentric circle.

The lens feed assembly **61** can be provided by a circular disk-shaped body **93** of 0.25 inch thick dielectric

material covered with a copper disk to form top wall **73** on one surface and a copper disk on the opposite surface to form bottom wall **95**, a copper covering being provided around the edge of the body to form the rim **97**. The dielectric body can be Z-tron-"G" material manufactured by the Polymer Corporation, Reading, Pa. The disk-shaped body **93** has a radius of 10.47 inches. The **48** outer probes **76** are arranged in a circle of a radius from the center of body **93** of 9.01 inches. The outer conductor **103** of each of the probes **76** is fixed to the top disk **73** as shown in FIG. **6**, and the inner conductors **105** extend in an insulative manner through an aperture **104** in the top conductor disk **73** and through the dielectric body **93**. The inner conductor **105** in this example extends all the way through the dielectric body **93** to the opposite conductive disk **95** at the opposite surface. In order to match the central and outer probes to the line formed, a 50-ohm conical taper **105***a* of the center conductor can be utilized as shown in FIG. **7**. The forty-eight (48) outer probes **76** are equally spaced on the 9.01 inch radius. The nine (**9**) central set of probes **75***a*, **75***b*, **75***c*, **75***d*, **75***e*, **75***f*, **75***g*, **75***h* and **75***j* are located near the center with probe **75***j* located at the center of the radial parallel plate line lens feed assembly **61** and the other eight probes **75***a*, **75***b*, **75***c*, **75***d*, **75***e*, **75***f*, **75***g* and **75***h* arranged in a circle of a radius of 1.65 inches about the center probe **75***j*. A description of the placement of the central probes **75***a* through **75***h* is achieved with the aid of placement lines **107** and **109** in FIG. **5**. Placement line **107** is drawn through the center of assembly **61** so as to divide the lens feed assembly **61** in half with line **107** running along cross section **6—6** through the center of the assembly. Line **109** is drawn to intersect line **107** at the center of the assembly **61** in FIG. **5** with line **109** orthogonal to line **107**. Probe **75***a* is located along a radius drawn at an angle of θ_1 to the left of line **107**. Probe **75***b* is located along a radius drawn at an angle of θ_1 to the right of line **107**. Similarly, probe **75***c* is located along a radius drawn at an angle of θ_1 to the left of line **107** and probe **75***d* is located along a radius drawn at an angle of θ_1 to the right of line **107**. In this example $\theta_1 = 29.50°$. Probe **75***e* is located along a radius drawn at an angle of θ_2 above line **109**. Probe **75***f* is located along a radius drawn at an angle of θ_2 below line **109**. Probe **75***g* is located along a radius drawn at an angle of θ_2 above line **109**. Probe **75***h* is located along a radius drawn at an angle of θ_2 below line **109**. In this example, θ_2 is equal to 29.50°. Probes **75***a* thru **75***h* are located about 1.65 inches from center probe **75***j*.

Referring to FIG. **4**, each of the 48 outer probes **76** is coupled to a separate phase shifter **64** via transmission line **66**. For purposes of illustration in FIG. **4**, only six probes (**76***a* thru **76***f*) of the outer probes **76** are shown connected to their appropriate phase shifters **64***a* thru **64***f* via lines **66**. Each of the four-way switches **67***a* thru **67***f* has the common terminal coupled to one of the outer probes **76***a* thru **76***f* respectively via lead **78** and four selectable terminals at the opposite end coupled to four separate radiating elements via leads **80**. These are four times as many radiating elements **65** as there are outer probes **76** ($48 \times 4 = 192$). The four radiating elements **65** coupled to each four-way switch **67** are equally spaced about the total array structure **63**. For example, four-way switch **67***a* in FIG. **4** is coupled at the one common end to probe **76***a* of the outer probes **76** via phase shifter **64***a* and is coupled at the opposite selectable terminal end at a first terminal **85** to the particular North-pointing radiating element **68***a*. The second terminal **86** of four-way switch **67***a* is coupled to the particular East-pointing radiating element **69***a*. The third terminal **87** of switch **67***a* is coupled to the particular South-pointing radiating element **70***a*. The fourth terminal **88** of switch **67***a* is coupled to the particular West-pointing radiating element **71***a*.

Coarse scanning of the antenna array system **60** is achieved by rotating the generated beam within the lens feed assembly **61** and by switching the position of four-way switches **67** to couple the outer probes **76** to a selected one of the four radiating elements **65**. The switching is accomplished on an element-by-element basis as the beam is scanned about the system by switching out the element furthest from the direction of rotation and adding the next element in the direction of rotation via the four-way switches **67** as the beam is scanned about the array. Although the operation described herein is beam scanning, it is understood that the switching can be done in any desired order to achieve a desired beam direction.

FIG. **8** is a sketch illustrating the switching technique. For convenience of illustration, the array of radiating elements are placed in a straight line rather than curved. Also, for purposes of illustration, only the six outer probes **76***a*, **76***b*, **76***c*, **76***d*, **76***e*, and **76***f* of the **48** outer probes **76** and six switches **67***a*, **67***b*, **67***c*, **67***d*, **67***e* and **67***f* of the 48 four-way switches **67** are illustrated. As described above, the outer probes **76** of the lens feed assembly **61** are coupled so that each outer probe **76** (48 in number) is coupled to a four-way switch **67** (48 in number) via a phase shifter **64**. As mentioned previously, the four-way switch **67***a* coupler energy between outer probe **76***a* and radiating elements **68***a*, **69***a*, **70***a* and **71***a*. Similarly, four-way switch **67***b* couples energy between outer probe **76***b* and radiating elements **68***b*, **69***b*, **70***b* and **71***b*; four-way switch **67***c* couples energy between probe **76***c* and radiating elements **68***c*, **69***c*, **70***c* and **71***c*; four-way switch **67***d* couples energy between probe **76***d* and radiating elements **68***d*, **69***d*, **70***d* and **71***d*; four-way switch **67***e* couples energy between probe **76***e* and radiating elements **68***e*, **69***e*, **70***e* and **71***e*; and four-way switch **67***f* couples energy between probe **76***f* and radiating elements **68***f*, **69***f*, **70***f* and **71***f*.

To achieve a beam directed to the northeast as indicated by arrow **73**, for example, the switches **67***a* thru **67***f* are energized by a control source **87** via leads **84** to switch all of the outputs from outer probes **76***a* thru **76***f* to radiating elements **68***a* thru **68***f* via the leads **78** and **80** and phase shifters **64**. The central set of probes **75***j* and **75***a* thru **75***h* are energized to produce a first cardioid pattern (shown by dashed line **81** in FIG. **8**) with the maximum power divided between the outer probes **76***c* and **76***d* and lesser symmetrical powers to the outer probes **76***b* and **76***e*. Little or no appreciable power exists at the outer probes **76***a* and **76***f*. This results in an output power distribution indicated by dashed curve line **82** in FIG. **8** with the four-way switches **67***a* thru **67***f* in the position to couple the power at probes **76***a* thru **76***f* to radiating elements **68***a* thru **68***f*. This produces a beam with maximum energy in the direction of arrow **73**. Since the power to the other radiating elements **69***a* thru **69***f*, **70***a* thru **70***f* and **71***a* thru **71***f* are completely switched out, no power is

radiated from these elements and therefore no side or back lobe signals emit from these other elements **65**, greatly reducing the possibility of back or side lobes. Also, a greater percentage of the wave energy generated by central probe **75** is this system is utilized in achieving the desired beam than in the system of FIg. **1**.

In commutating the beam about the array **60**, the FIG. switches **67***a* thru **67***f* are sequentially switched element by element from the series of radiating elements **68** to the series of radiating elements **69**, from the series of radiating elements **69** to the series of radiating elements **70**, from the series of radiating elements **70** to the series of radiating elements **71** and from the series of radiating elements **71** back to the series of radiating elements **68**. In scanning clockwise, the switches are energized in the sequence **67***a*, **67***b*, **67***c*, **67***d*, **67***e*, **67***f* and back to **67***a*. For example, to achieve scanning from the northeast radiated position, indicated by arrow **73**, to the east position indicated by arrow **83**, the radiated power distribution at the particular outer probes **76***a* thru **76***f* is altered with adjustment of the power and phase at inner probes **75** and the selected position of the four-way switches **67***a*, **67***b* and **67***c* are switched to couple power from the probes **76***a*, **76***b* and **76***c* to antenna radiating elements **69***a*, **69***b* and **69***c*. The central set of probes **75** have their power distribution altered as indicated by pattern **81***a* so that the maximum power is centered at outer probe **76***a* with equal power at the probes **76***b* and **76***f*. A negligible low power level exists at probes **76***c* and **76***e* and a minimum power level exists at probe **76***d*. The result is a power distribution as indicated by curved dashed line **83** and a radiated beam with the main lobe pointing in the East direction of arrow **85**. Coarse beam scanning is thereby done as discussed previously by switching "on" sequentially the antenna elements **70***a*, **70***b*, **70***c*, **70***d*, **70***e* and **70***f* while switching "off" sequentially elements **69***a*, **69***b*, **69***c* . . . **69***f*. A complete 360° scan is achieved by switching "on" elements **71***a*, **71***b*, **71***c* . . . **71***f* while switching "off" **70***a*, **70***b*, **70***c* . . . **70***f* and then switching "on" **68***a*, **68***b*, **68***c* . . . **68***f* while switching "off" elements **71***a*, **71***b*, **71***c* . . . **71***f*. While this switching is being done, the cardioid pattern is being rotated within the lens feed assembly **61**.

The fine steering to provide collimation and a continuous scan is achieved by the phase shifters **64** located between each four-way switch **67** and the outer probes **76**. Control signals to the phase shifter **64** and switches **67** are provided by a control signal from source **87** via leads **84***a*.

The desired rotatable cardioid-like pattern as illustrated and discussed in connection with FIG. **8** is provided by generating two rotating phase omnidirectional patterns of reciprocal phase rotation represented by patterns **106** and **108** in FIG. **9** and by combining these with a uniform phase omnidirectional pattern as represented by pattern **113** in FIG. **9**. The phase at the one rotating phase omnidirectional pattern **106**, for example, goes clockwise from 0° to 90°, 90° to 180°, 180° to 270° and 270° to 360° as shown in FIG. **9**. The phase at the other rotating omnidirectional pattern **108**, for example, goes clockwise from 0° to 270°, 270° to 180°, 180° to 90° and 90° to 0° as shown in FIG. **9**. Combining these two counter rotational phase patterns results in a figure-eight pattern. By adjusting the phase between the two counter rotating omnidirectional patterns so that one is given a positive (+) ϕ and the other given an equal negative (−) ϕ, the orientation of the figure-eight pattern can be selectably positioned in any given direction. For example, by adding a $\phi = +30°$ to one rotating omnidirectional pattern to achieve the phase rotation shown in FIG. **10**, the other rotating omnidirectional pattern should have a $-\phi$ or $-30°$ to achieve the other rotating phase omnidirectional pattern as shown in FIG. **11**. In this case the orientation of the figure-eight pattern is rotated approximately 30°. Each of these two counter rotating phase omnidirectional patterns is generated by two figure-eight patterns of equal power and at phase quadrature.

FIG. **12** illustrates the feed system **117** for properly exciting the inner probes **75** to produce the selected cardioid type energy distribution within the parallel plate line lens feed assembly **61** and to commutate these distributions within the assembly **61** by means of phase settings to the phase shifters.

The center probe **75***j* in FIGS. **5** and **12** excites a uniform phase omnidirectional radial pattern within the radial parallel plate transmission line lens feed assembly **61**. Each of probes **75***a* and **75***b* are excited at a given phase and probes **75***c* and **75***d* are excited with equal power as probes **75***a* and **75***b* but at a 180° phase difference to produce the first figure-eight pattern as illustrated by line **110** in FIG. **13**. The probes **75***e* and **75***f* are excited with equal power and in phase. The phase of the signals at probes **75***e* and **75***f* are at phase quadrature with the phase of the signals at probes **75***a* and **75***b* . Probes **75***g* and **75***h* are excited with equal power as probes **75***e* **75***f* but at a 180° phase difference to provide the second figure-eight pattern in phase quadrature as illustrated by line **111** in FIG. **13**.

Referring to FIG. **12**, the probes **75***a* and **75***b* are coupled to arms **120***a* and **120***b* of hybrid **120**. The hybrids herein may be, for example, rat race hybrids. The summing lead **120***c* of hybrid **120** is coupled to hybrid **125** at arm **125***a*. The difference lead **120***d* of hybrid **120** is open circuited at the end. Similarly, probes **75***c* and **75***d* are coupled respectively to arms **121***a* and **121***b* of hybrid **121**. The summing arm **121***c* of hybrid **121** is coupled to hybrid **125** at arm **125***b*. The difference lead **121***d* of hybrid **121** is open circuited at the end. The summing arm **125***c* of hybrid **125** is terminated in an open circuit, and the difference arm **125***d* is coupled to point **126**. Signals coupled at point **126** are divided equally at hybrid **125** with the signals applied to hybrid **120** being 180° out of phase with respect to those at hybrid **121**. This phase and power relationship provides for the first figure-eight pattern **110** in FIG. **13**.

Similarly, probes **75***e* and **75***f* are coupled to arms **127***a* and **127***b* respectively of hybrid **127**. The summing arm **127***c* of hybrid **127** is coupled to arm **131***a* of hybrid **131**. The difference arm **127***d* is terminated in an open circuit. The probes **75***g* and **75***h* are coupled to arms **129***a* and **129***b* respectively of hybrid **129**. The summing arm **129***c* of hybrid **129** is coupled to arm **131***b* of hybrid **131**. The difference arm **129***d* is terminated in an open circuit. The summing arm **131***c* is terminated in an open circuit and the difference arm **131***d* is coupled to point **128**. A signal at point **128** is coupled equally to hybrids **127** and **129** with the signals coupled to hybrid **127** being 180° out of phase with respect to signals coupled to hybrid **129**. This phase and power

relationship provides for the second figure-eight pattern.

The two rotating omnidirectional patterns **106** and **108** in FIG. **9** with opposite phase rotation is provided by coupling the 3 db 90° (quadrature) coupler **140** between the points **126** and **128** at one end and the points **141** and **143** at the opposite end. One half the signal at point **141** is coupled to point **126** and the other half of the signal is phase shifted 90° to point **128.** Similarly, half of the signal at point **143** is coupled to point **128** and the other half of the signal is coupled to point **126** with 90° phase shift. In the case of reciprocal operation signals at either points **126** or **128** are equally divided and coupled 90° out of phase to points **141** and **143.**

By adjusting the relative phase shift of the two rotating omnidirectional patterns, as mentioned previously, the adjustable direction figure-eight pattern is provided. This adjustment of relative phase shift is accomplished by phase shifters **145** and **147** located between hybrid **149** and points **141** and **143.** The phase adjustment of phase shifters **145** and **147** is made so that phase shifter **145** be made to provide a negative (−) ϕ phase shift, for example −30°, when phase shifter **147** provides a positive (+) ϕ or in the example +30°. The result is the two counter rotating phase omnidirectional patterns in FIGS. **10** and **11** and a resultant figure-eight pattern. The summing arm **149***c* of hybrid **149** is coupled to port **151** of directional coupler **150.** The difference arm **149***d* is coupled to difference port **157.** The signal information at this difference arm **149***d* is that from a figure-eight pattern orthogonally oriented to the selected figure-eight pattern as illustrated by pattern **118** in FIG. **9.** To achieve the desired cardioid shape, the uniform phase omnidirectional pattern (represented by pattern **113** in FIG. **9**) is added to the selectable figure-eight pattern. The power ratio of the uniform phase omnidirectional pattern **113** relative to the figure-eight pattern is in the order of 3 to 1. This can be achieved by a 6 db directional coupler **150** whereby 75 percent of the power at sum terminal **155** is applied to terminal **153** of coupler **150** and 25 percent of this power is applied to sum port **149***c* of hybrid **149.** The result is a selected cardioid pattern illustrated by pattern **119** in FIG. **9.** At the difference arm **149***d* of hybrid **149** is provided the results of a figure-eight pattern illustrated by pattern **118** with the null pointing in the direction of the maximum signal strength of the selected cardioid-like pattern **119** as shown in FIG. **9.**

It is understood that the well known reciprocal theory of antennas applies and whatever performs for generating a radiated pattern performs in the reverse when a radiated pattern is received.

A difficulty may be encountered due to cross coupling between the inner probes **75.** Isolation between points **126** and **128** and point **130** along center probe **75**j is had by adjusting the lengths of the difference arm stubs **120***d*, **121***d*, **127***d* and **129***d* in hybrids **120, 121, 127** and **129** and the summing arm stubs **125***c* and **131***c* in hybrids **125** and **131.** The adjustment of the length of these stubs is done empirically by varying the stub lengths until minimum cross coupling occurs.

The above-described parallel plate line lens feed assembly **61** including the feed distribution network **117** in FIG. **12** was built and tested over a frequency range of 1,250 – 1,325 MHz. With ϕ equal to 0° (zero degrees phase shift) at phase shifter **145** and **147** the peak of the sum distribution (maximum field strength) of the cardioid-like pattern was aligned with the sixth probe **76** to the right of outer probe **76***a*. Also the null of the difference distribution was aligned with this same sixth probe to the right of probe **76***a*. When $\phi = 80°$ is applied to phase shifter **147** and $-\phi = -80°$ is applied to phase shifter **145,** the pointing direction changed with the peak of the cardioid-like pattern (maximum field strength) pointing between the sixteenth and seventeenth probe to the right of probe **76***a*. The amplitude and phase levels did not change as the distribution was commutated.

In optimizing the system, the central set of probes **75***a* thru **75***h* are arranged with a degree of arc ($2\theta_1$ for example) between the probes of a pair being between 50° and 70°. Further in optimizing the system the radius or distance from the center probe **75***j* to one of the other central set of probes **75***a* thru **75***h* is between 0.2 to 0.4 wavelengths in the dielectric medium of the assembly **61.**

In accordance with another embodiment shown in FIG. **14** of the present invention, the assembly **161** includes a central set of five probes **175.** The five probes are arranged as shown in FIG. **14** with a central probe **175***j*. The paired probes in FIG. **5** are replaced by single probes **175***a* thru **175***d* placed on a line bisecting the arc of the replaced probes **75** in FIG. **5** and located considerably closer to the center probe **175***j*.

What is claimed is:

1. A ring-like antenna array system comprising:

a pair of parallel overlapping conductive plates spaced from each other with a dielectric medium therebetween to form a transmission line,

a first plurality of probes being arranged in a ring-like pattern near the periphery of the parallel overlapping conductive plates, each of said first plurality of probes having a portion hereof extending into the field region of said transmission line,

means including a second plurality of probes being grouped in a pattern near the center of said parallel conductive plates for generating a radiated pattern of electromagnetic energy with a selected amplitude distribution of that energy within said transmission line to thereby excite a given group of said first plurality of probes,

a plurality of radiating elements arranged in a ring-like pattern, the number of said radiating elements being N times as many elements as there are probes in the first plurality of probes, where N is an integer greater than one,

a plurality of N-way switches, said switches being equal in number to said first plurality of probes,

each of said N-way switches being electrically coupled to a different one of said first plurality of probes, N number of said radiating elements being selectively coupled to each N-way switch, said N radiating elements coupled to each switch being equally spaced about the array,

and means for changing the selected switch positions of said N-way switches to determine the radiating elements electrically coupled to each of said first plurality of probes and thereby control with the generating means the direction of the beam radiated from the system.

2. The combination of claim **1** including collimating means coupled between said first plurality of probes and said N-way switches.

3. The combination in claim **2** where N is four.

4. The combination in claim 2 wherein said collimating means includes a variable phase shifter coupled between each N-way switch and one of said first plurality of probes.

5. The combination in claim 1 wherein said means for generating a radiated pattern within said transmission line includes a power distribution network so arranged as to produce a rotatable cardioid-like pattern and a difference mode pattern within the region bounded by the plates.

6. The combination in claim 5 wherein said means for generating said rotatable cardioid-like pattern further includes a pair of phase shifters and a coupler, a first of said phase shifters being arranged to provide a phase shift equal in phase shift but of opposite sign to that provided by the second of said phase shifters.

7. The combination in claim 6 wherein said coupler is arranged to combine the power of a fixed omnidirectional pattern and the resultant power from said two counter rotating omnidirectional patterns.

8. The combination in claim 1 wherein said second plurality of probes is five probes with one central probe and four probes arranged in a circle coaxially with the central probe.

9. The combination in claim 1 wherein said second plurality of probes is nine with one center probe and eight probes arranged in a circle coaxially with the center probe.

10. The combination in claim 9 wherein said eight coaxially arranged second plurality of probes are distributed in pairs such that each pair is 90° of arc from the next adjacent pair of probes.

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