ANTENNA SYSTEM FOR RADIATING DIRECTIONAL PATTERNS

Original Filed Nov. 16, 1961 3 Sheets-Sheet 1

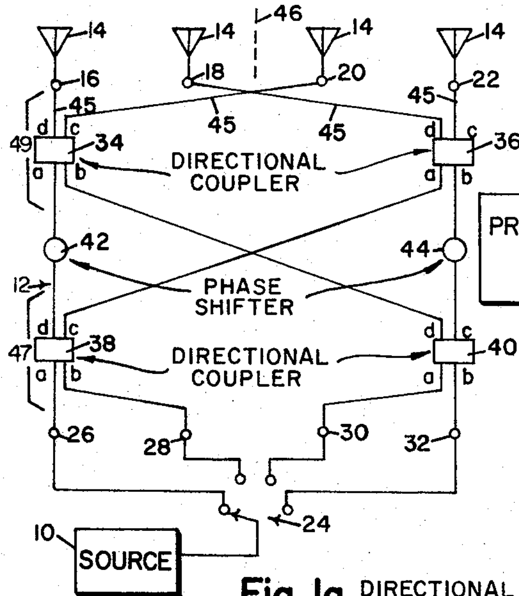


Fig. 1a

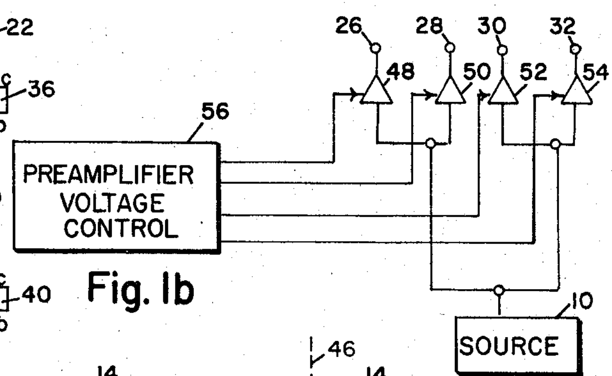


Fig. 1b

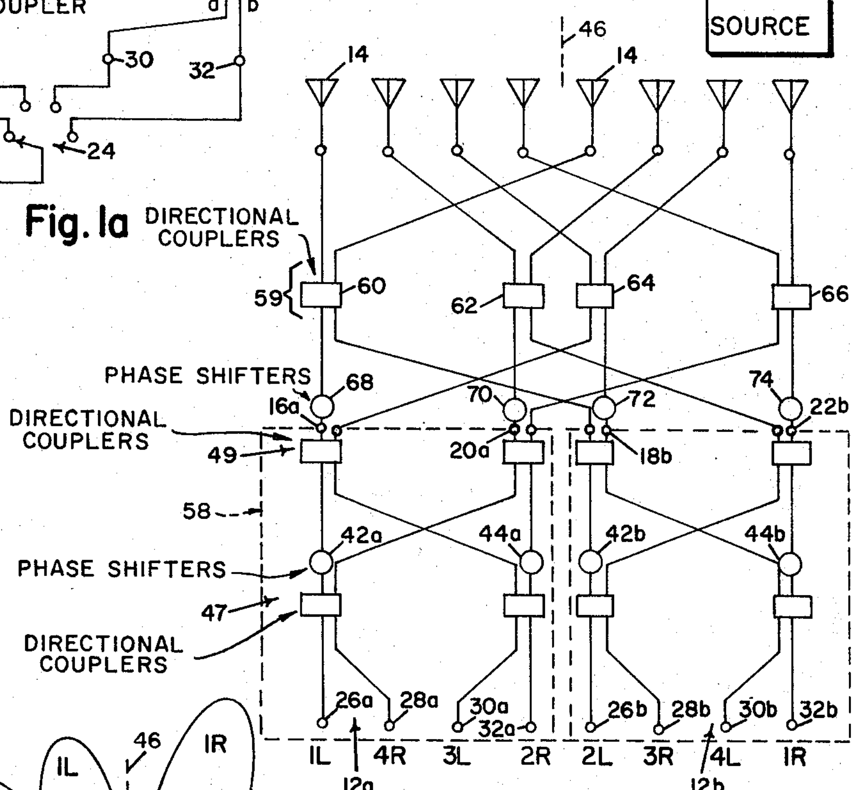
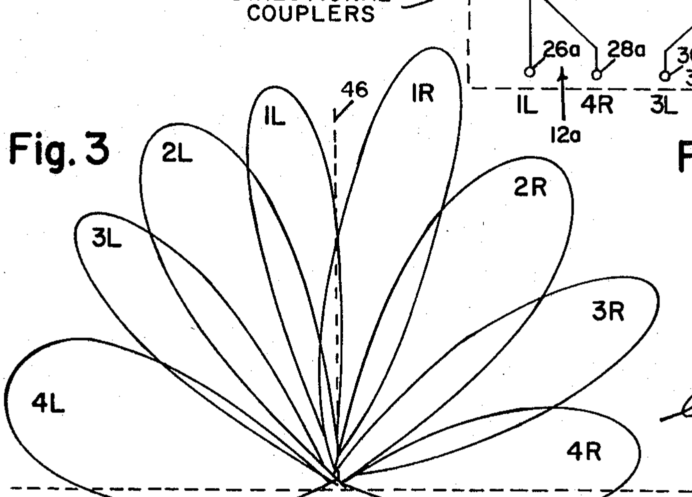


Fig. 2

Fig. 3



William R. Lowe
INVENTOR
Robert O. Richardson
ATTORNEY

ANTENNA SYSTEM FOR RADIATING DIRECTIONAL PATTERNS

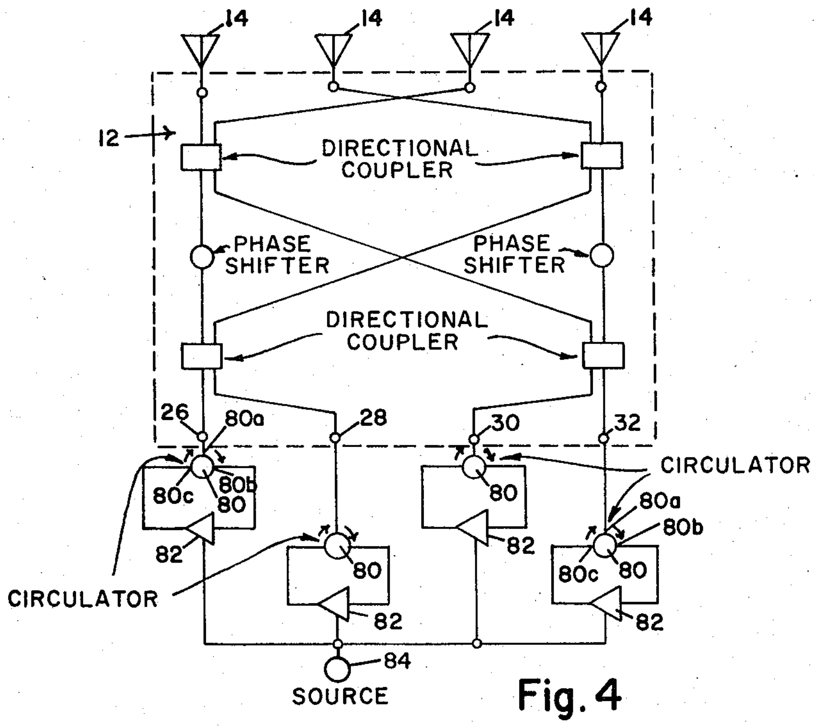


Fig. 4

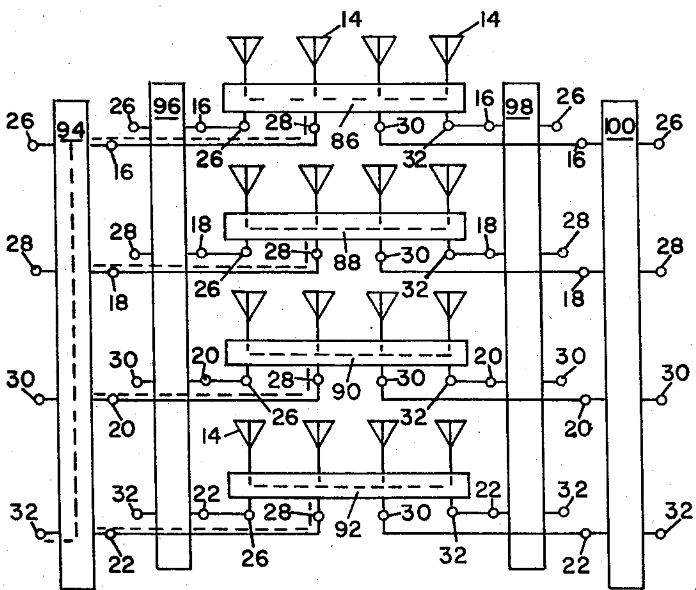


Fig. 5

William R. Lowe
INVENTOR
Robert O. Richardson
ATTORNEY

ANTENNA SYSTEM FOR RADIATING DIRECTIONAL PATTERNS

Original Filed Nov. 16, 1961 3 Sheets-Sheet 3

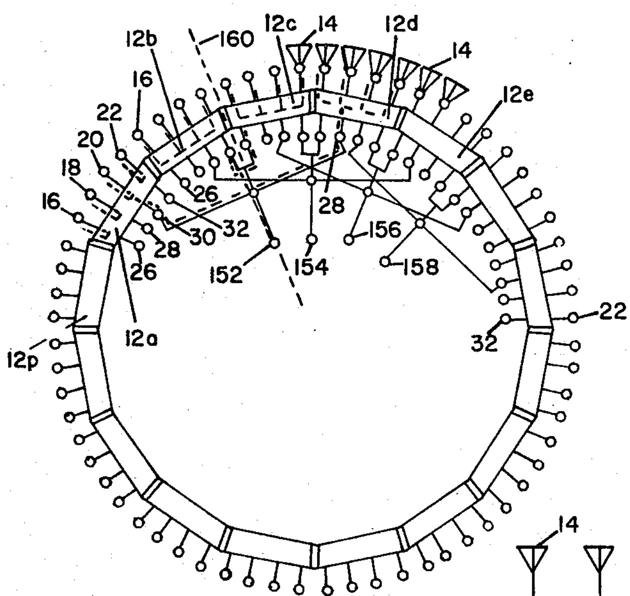


Fig. 6

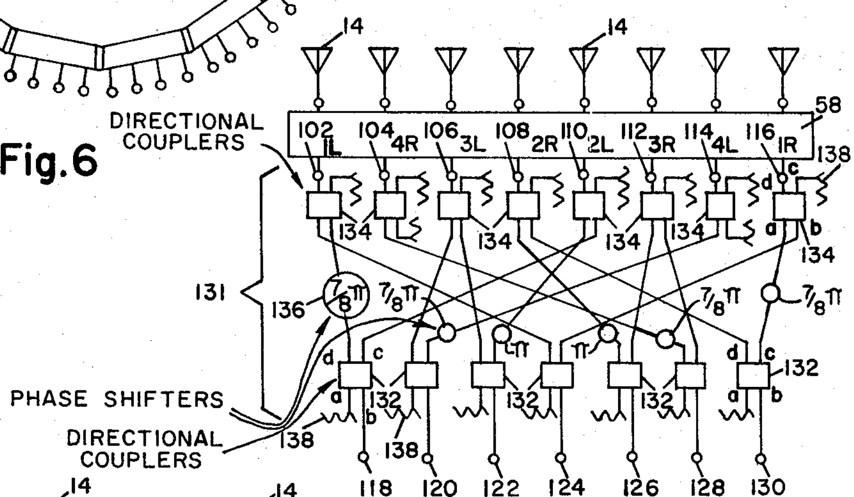


Fig. 7

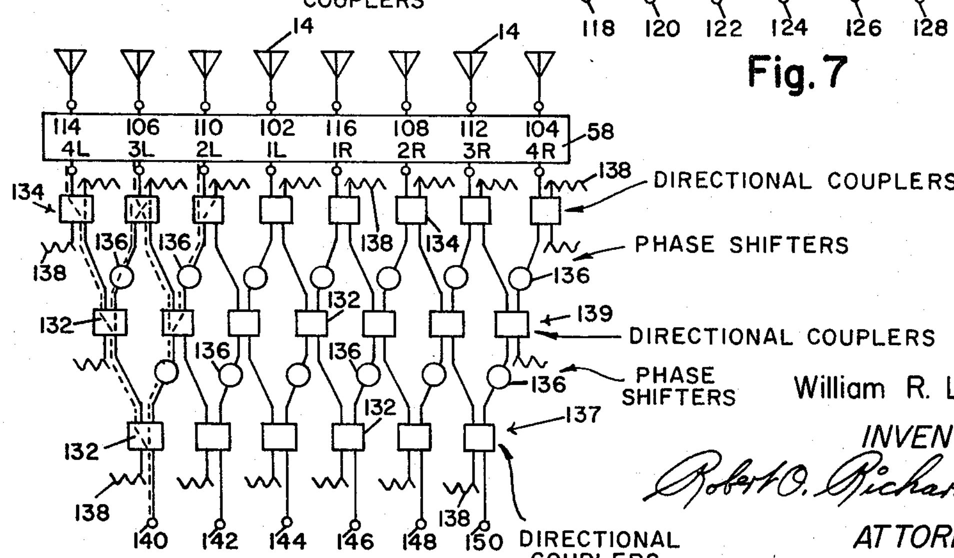


Fig. 8

William R. Lowe
INVENTOR

Robert O. Richardson
ATTORNEY

United States Patent Office 3,295,134
Patented Dec. 27, 1966

1

3,295,134
ANTENNA SYSTEM FOR RADIATING DIRECTIONAL PATTERNS

William R. Lowe, Nashua, N.H., assignor to Sanders Associates, Inc., Nashua, N.H., a corporation of Delaware
Continuation of application Ser. No. 152,762, Nov. 16, 1961. This application Nov. 12, 1965, Ser. No. 507,513
17 Claims. (Cl. 343—100)

This application is a continuation of application Serial No. 152,762, filed November 16,1961, and now abandoned.

This invention relates to directional antenna systems. More specifically, it relates to a novel transmission network for feeding a stationary array of antenna elements to radiate directional patterns. The network, comprising only passive components, combines four-port couplers with fixed phase shifters to achieve beam-steering merely by applying an input signal to different individual input ports. The antenna system is reciprocal, i.e., it can be used for receiving or transmitting, and has a minimum loss. Thus, it provides highly reliable and efficient antenna beam steering and is suitable for both high and low power applications.

In general, stationary antenna arrays having a steerable radiation pattern comprise antenna elements energized with a uniform phase gradient between them. The amount and direction of the phase difference between adjacent elements determines the direction of the radiation pattern. Prior antenna array systems generally comprise a plurality of three-port couplers, such as two-to-one power dividers interconnected in a tree-like network to channel input energy, delivered at a single input port, to the antenna elements. Variable phase shifters are connected between the couplers to insert the phase delay required to steer the beam in the desired direction. These systems generally require an excessive number of phasing components and couplers and, in addition, require control apparatus to adjust the delay inserted by each of the variable phase shifters, in order to steer the beam in the desired direction. Further disadvantages are the requirement for active components in the phase control apparatus and the inability to simultaneously generate several directional patterns, the latter often being a desirable feature.

The radiation pattern of an antenna generally has a main lobe and one or more minor or side lobes. It is sometimes desirable to concentrate the energy in the main lobe, thereby decreasing the side lobe level. In addition, when the level of a side lobe is comparable to the main lobe, it is often difficult or impractical to distinguish signals in the main lobe from signals in the side lobe. Accordingly, low side lobe levels are desired to reduce the potential ambiguity between the main lobe and the side lobe signals.

Side lobe effects may be reduced by feeding the antenna elements so that the elements in the center of the array radiate more energy than do the elements near the edges. In other words, the amplitudes of the currents fed to the antenna elements are tapered, with the elements in the center of the array receiving more current than those at the edges of the array.

Prior apparatus for achieving decreased side lobe levels includes the use of attenuators to reduce the current fed to the elements at the edges of the array, and the use of electronic devices such as amplifiers to feed currents having different amplitudes to the several elements. However, the use of attenuators results in excessive losses in the system while the active electronic devices are often costly and complex, in addition to being bulky, heavy and somewhat unreliable. Furthermore, the electronic apparatus generally operates at an intermediate frequency, different than the frequency of the energy to be transmitted and, accordingly, requires additional electronic equipment to convert the intermediate frequency signals to the desired carrier frequency and vice versa.

2

Accordingly, it is a principal object of this invention to provide an improved directional antenna system.

Another object of the invention is to provide a phasing network, for use in directional antenna systems, that incorporates only passive components.

A further object is to provide an antenna system that does not require phase shifter adjustments to steer the radiation pattern. A corollary object is to provide a directional antenna system, having steerable radiation patterns, that is reliable and suitable for remote installation.

Yet another object is to provide an improved antenna system that is capable of illuminating several selectable directional patterns simultaneously.

Still another object of the invention is to provide an antenna system of the foregoing type that produces radiation patterns having low side lobe levels.

A further object of this invention is to provide improved transmission apparatus for feeding an antenna array to radiate directional patterns.

Yet another object of the invention is to provide an antenna system of the above description that has low loss and requires fewer components than prior antenna systems of this type.

Still another object is to provide transmission apparatus, for feeding a directional antenna array, that is simple to construct and requires minimum space.

Other objects of the invention will in part be obvious and will in part appear hereinafter.

The invention accordingly comprises the features of construction, combination of elements and arrangement of parts which will be exemplified in the constructions hereinafter set forth and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention, reference should be had to the following detailed description taken in connection with the accompanying drawings, in which:

FIG. 1*a* is a schematic diagram, partly in block form, of an antenna system embodying the invention,

FIG. 1*b* is a block diagram of a circuit for energizing the antenna system of FIG. 1*a*,

FIG. 2 is a block diagram of another antenna system embodying the invention,

FIG. 3 is a simplified graph showing the directional radiation characteristics of the antenna system of FIG. 2,

FIG. 4 is a block diagram of a transponder system embodying the invention,

FIG. 5 is a block diagram of an antenna system for steering a radiation pattern in both elevation and azimuth,

FIG. 6 is a fragmentary block diagram of a circular array antenna system embodying the invention,

FIG. 7 is a schematic diagram, partly in block form, of an antenna system for radiating directional patterns with diminished side lobe levels, and

FIG. 8 is a schematic diagram, partly in block form, of another antenna system for radiating directional patterns having substantially reduced side lobes.

The present antenna system comprises a succession of antenna elements energized through a transmission network that imparts a uniform phase difference to the currents fed to adjacent elements. The network comprises four-port directional couplers interconnected with fixed phase shifters to provide transmission paths from each of a plurality of input ports to all the antenna elements. The transmission paths between each input port and the antenna elements have different electrical lengths to provide the desired phase gradient between the elements. Because of the directional nature of four-port directional couplers, the network provides isolation between the input ports and also between the output ports, to which the elements are connected.

Couplers of this type can also serve as power dividers with fixed phase differences between signals emanating therefrom. By combining the couplers with fixed phase shifters, the network provides different phase gradients between adjacent output ports, according to which input port is energized. Thus, the array radiates in different directions when input energy is applied to different input ports. In the basic array, a signal applied to an input port is transferred with equal amplitude to all output ports.

The currents fed to the antenna elements have a cosine amplitude distribution, to obtain diminished side lobe levels, when two input ports that generate adjacent patterns are energized simultaneously with signals phased so that the two patterns partially coincide. The currents fed to the antenna elements have a cosine^2 distribution when the input signal is divided into three components and delivered simultaneously to three input ports. The three components are phased and adjusted in amplitude so that the three patterns generated have the same phase center and form a single resultant pattern having low side lobe levels.

More specifically, the antenna system shown in FIG. 1*a* comprises a source **10** that delivers radio-frequency energy to a four-port network, indicated generally at **12**. The network **12** transfers the energy to antenna elements **14—14** connected to a succession of network output ports **16**, **18**, **20** and **22**. A switch, generally indicated at **24**, connects to respective network input ports **26**, **28**, **30** and **32**. The network **12** comprises identical transmission line directional couplers **34**, **36**, **38** and **40**, and phase shifters **42** and **44**, interconnecting the input ports with the output ports. The network imparts a uniform phase difference to the signals delivered to adjacent output ports to cause the antenna pattern radiated by the elements **14** to be directional. The magnitude and direction of the phase gradient between consecutive output ports has different values when the switch **24** connects the source **10** to different input ports **26**, **28**, **30** and **32**, to thereby steer the radiation pattern in different directions.

The couplers **34**, **36**, **38** and **40** are four-port, 3 db directional couplers having fixed phase differences between their output ports. A signal fed to one of the four ports is divided into two equal output signals appearing at the two opposite ports. With quarter-wave parallel line directional couplers, the output signals differ in relative phase by 90°, with the output port diagonally opposite the input port having the greatest delay, equal to 180°. For example, a signal fed in at port *a* of the coupler **34** is transferred equally to port *c* and *d*, with the energy delivered to the port *c* delayed 180° relative to the phase at port *a* and the energy delivered to port *d* delayed 90°. The couplers provide substantial isolation between the *a* and *b* ports and also between the *c* and *d* ports. Preferably, they are of the parallel-line type, although branch-line couplers may also be used where narrow band operation is contemplated. Hybrid rings, or magic tee, which have a 180° phase difference between the two output signals, may also be used in the network **12**. In any case, the terms "coupler," and "power divider," as used herein, mean devices having the above characteristics.

Still referring to FIG. 1*a*, the input ports **26** and **28** are connected to the coupler **38**, and the ports **30** and **32** are connected to the coupler **40**. The couplers **34** and **36** each receive signals from both couplers **38** and **40**, as shown in the drawing. The transmission lines **45—45**, between the output ports **16**, **18**, **20** and **22** and the couplers **34** and **36**, preferably have the same electrical lengths to preserve the relative phase difference between signals imparted by the couplers and the phase shifters.

Likewise, transmission lines of equal electrical length interconnect the couplers. Thus, the only differential phase delays in the network, between its input ports and output ports, are provided by the couplers and the phase shifters. The phase shifters may, of course, be differential lengths of transmission line in narrow band applications. However, for wide band operation devices, well known in the art, providing phase shifts constant over a wide range of frequencies should be used. For the embodiment of FIG. 1*a*, the phase shifters **42** and **44** are characterized by a fixed delay of 45°.

The couplers are arranged in stages, with the couplers **38** and **40** comprising a first stage **47**, and the couplers **34** and **36** a second stage **49**. It should be noted that the couplers in the stage **49** interconnect output ports spaced $n/2$ ports apart, where n is the number of output ports.

To consider operation of the network **12**, assume first that the source **10** delivers a signal having an amplitude A to the input port **26**. The relative phases and amplitudes of the signal emanating from the coupler **38** are:

Port 38*d* ----------------------------	A/2 at 90°.
Ports 38*c* and 36*a* --------------------	A/2 at 180°.

After passing through the phase shifter **42**, the relative phase and amplitude of the affected signal is

Port 34*a* ----------------------------	A/2 at 135°.

The relative phases and amplitudes of the signals delivered to the output ports from the couplers **34** and **36** are then:

Port **16** ----------------------------	A/4 at 225°.
Port **18** ----------------------------	A/4 at 270°.
Port **20** ----------------------------	A/4 at 315°.
Port **22** ----------------------------	A/4 at 360°.

Thus, signals having equal amplitudes excite the elements **14** with equal phase differences between adjacent elements.

Accordingly, when the antenna elements are spaced a half wavelength apart at the operating frequency and the network is energized at input port **26**, the antenna elements radiate in a directional pattern aimed 13° to the right of an array axis 46 normal to the array of elements.

When switch **24** is set to deliver the source energy to input port **32**, the signals delivered to the antenna elements **14** are phased to produce an identical radiation pattern symmetrically oriented on the left of the axis **46**, i.e., directed at −13°. When the input energy is delived to port **28**, the elements radiate in a directional pattern oriented approximately 48° to the left of the axis **46**, and when the input port **30** is energized, the resultant radiation pattern is 48° to the right of the axis **46**. The following table gives the relative beam positions, the relative phases of the signals at the elements **14** and the phase gradients that result when the input signal is fed to the respective input ports **26-32**.

Relative phase delay at output ports

Beam Position	Energized Input Port	16	18	20	22	Phase Gradient
1R	26	225	270	315	360	$+45°=\pi/4$.
2L	28	315	180	45	270	$-135°=-3\pi/4$.
2R	30	270	45	180	315	$+135°=3\pi/4$.
1L	32	360	315	270	225	$-45°=-\pi/4$.

When two or more input ports are energized simultaneously, the same number of radiation patterns exist simultaneously. Thus, the antenna system of FIG. 1*a* can easily be used to radiate beams in several directions simultaneously.

FIG 1*b* illustrates apparatus connected to the input ports **26**, **28**, **30** and **32** of the antenna system of FIG. 1*a* to provide efficient switching between the radiation patterns. The source **10** is connected simultaneously to four amplifiers **48**, **50**, **52** and **54**, whose output terminals are connected to the input ports **26–32**. The amplifiers are biased to an inoperative condition and thus they operate only when a control voltage is applied to them from a preamplifier voltage control unit **56**. To radiate the **1L** (One Left) pattern, for example, the preamplifier control unit **56** delivers a gating voltage to the amplifier **54** to render it operative, and the signal from the source **10** is then applied to the input port **32** of the network **12**.

Referring again to FIG. 1*a*, for transmitting high power, power amplifiers (not shown) may be connected between each output port **16–22** and the antenna element **14** connected therewith. This allows the antenna phasing and beam switching operations to be efficiently carried out at relatively low power levels, with relatively inexpensive transmission components. For example, the phasing network **12** can be fabricated in a single compact unit with strip transmission line, using parallel-line directional couplers incorporated in the line.

An antenna system for generating radiation patterns having greater angular resolution and a wider total coverage angle than the system of FIG. 1*a* is shown in FIG. 2. It comprises a network **58** composed of two four-port networks **12*a*** and **12*b***, each similar to the four-port network **12** of FIG. 1*a*. The output ports from the networks **12*a*** and **12*b*** are cross-coupled with a stage **59** of transmission line couplers **60**, **62**, **64** and **66**, preferably similar to the couplers used in the network **12**. The phase shifters **44*a*** and **42*b*** are characterized by a fixed phase delay of 22½°, and the shifters **42*a*** and **44*b*** have a delay of 67½°. Phase shifters **68**, **70**, **72** and **74**, imparting a 45° fixed phase shift, are connected between the output ports **16*a***, **20*a***, **18*b*** and **22*b*** and the couplers **60**, **62**, **64** and **66**, respectively, as shown.

The network **58**, having eight input ports and eight output ports, is capable of feeding the antenna elements **14** with signals phased to radiate in eight different directional patterns, the main lobes of which are represented graphically in FIG. 3. The patterns are designated **1R**, **2R**, **3R**, etc., corresponding to positions One Right, Two Right, Three Right, etc., with respect to the array axis **46**. In FIG. 2, the network input ports are similarly designated to indicate to which input port the transmitter energy should be delivered to illuminate the desired radiation pattern. The phase gradient between the adjacent antenna elements **14**, and the orientation of the radiation patterns relative to the axis **46**, obtained when signals are fed to the respective input ports of the network **58**, are presented in Table II for a half wavelength spacing between antenna elements.

TABLE II

Radiation Patterns	Energized Input Port	Phase Gradient		Pattern Orientation, for λ/2 spacing between Adjacent Elements, Degrees
		Rad.	Degrees	
4L	30b	$14\pi/16$	157½	−61
3L	30a	$10\pi/16$	112½	−39
2L	26b	$6\pi/16$	67½	−22
1L	26a	$2\pi/16$	22½	−7
1R	32b	$-2\pi/16$	−22½	+7
2R	32a	$-6\pi/16$	−67½	+22
3R	28b	$-10\pi/16$	−112½	+39
4R	28a	$-14\pi/16$	−157½	+61

More generally, antenna systems embodying the present invention can be constructed to energize an array of 4, 8, 16, 32, etc., antenna elements (i.e., 2^n where n is any positive integer) and develop the same similar number of directional radiation patterns. A system for radiating n independent beams has n input ports and incorporates a phasing network comprising $(n/2 \log_2 n)$ four-port couplers plus a smaller number of fixed phase shifters, each characterized by a phase shift of a multiple of π/n radians.

When the couplers are quarter-wavelength, parallel-line couplers which have an inherent 90° phase difference between the output arms, the location of any beam can be obtained from the expression

$$\sin \theta = \frac{2k-1}{nd_r} \pi \qquad (1)$$

where,

d_r is the element spacing in radians,

θ is the angle between the array axis **46** and the radius vector bisecting the main lobe of the beam, and

k is the beam index number equal to 1, 2, 3, . . . $n/2$.

The Equation 1 reduces to:

$$\sin \theta = \pm \frac{2k-1}{n}$$

when the element spacing is one half wavelength, (λ/2).

The networks are constructed using as sub-networks one or more of the four-port, four-coupler networks **12** (FIG. 1*a*), arranged with their input ports **26–32** constituting the input ports of the desired network. To construct an eight-port, eight-beam network, as shown in FIG. 2, two four-port networks **12** of FIG. 1*a* are arranged with their output ports interconnected with four couplers constituting the last stage thereof. A 16-port, 16-pattern network comprises four four-port networks, arranged first in two eight-port networks, similar to the network **58**, whose output terminals are then cross-coupled with eight additional couplers.

Phase shifters are inserted between the coupler stages in each successive pair thereof, with the number of phase shifters equal to the number of couplers in each of the two stages, i.e., one half the number of inter-stage connections. The phase shifters between the last two stages have a fixed phase delay of 45°. In the network **58** of FIG. 2, for example, the phase shifters **68–74** between the stages **49** and **59** have a 45° phase delay. The phase characteristics of the remaining phase shifters may easily be determined arithmetically by computing the phase of delays necessary to obtain the desired phase gradient between successive output ports, as given, for example, by Equation 1.

A four-beam transponder, or beacon system, shown in FIG. 4, comprises the network **12** with antenna elements **14**. A three-port circulator **80**, an amplifier **82** and a common source **84** are connected to each of the network input ports **26–32**. A signal input to any one of the circulator ports **80*a***, **80*b*** or **80*c*** is transferred by the circulator to the next clockwise-adjacent port thereto, and is isolated from the other circulator port. Radio-frequency signals received by the antenna elements **14** are coupled through the network **12** and delivered to the input ports **26–32**, with the relative amplitudes at these ports depending on the direction from which the signals arrive. The signals are delivered to the corresponding circulator ports **80*a***, and the transponder system then transmits a reply signal in the direction from which the incoming signal was received.

More specifically, the energized circulators **80** transfer the received signals from their port **80*a*** to the ports **80*b***, which are connected to the input terminals of the amplifiers **82**. The received signals control the amplifiers **82** to cause corresponding amplification of the output of the source **84** and consequent generation of a reply signal which is delivered to the circulator ports **80*c***. The circulators couple the energy from the ports **80*c*** to the ports

80*a* and deliver it to the same network input ports at which the received signals appeared. Accordingly, the antenna system transmits the reply signal in the direction from which the interrogate signal was received.

Since the antenna system comprising the network **12** and elements **14** is capable of transmitting or receiving multiple beams simultaneously, as mentioned above, the transponder of FIG. 4 can respond to several interrogations received simultaneously from plural directions.

Referring to FIG. 5, an elementary antenna system for steering radiation patterns in both elevation and azimuth comprises four azimuth-steering four-port networks **86**, **88**, **90** and **92**, shown in block form, each similar to the network **12** of FIG. 1*a*, and four similar networks **94**, **96**, **98** and **100**, for elevation steering. Antenna elements **14** are connected to the output ports of the networks **86–92**, and the output ports **16–22** of the networks **94–100** are connected to the input ports **26–32** of the networks **86–92**. Connections to a transmitter or a receiver (not shown) are made at the input ports **26–32** of the networks **94–100**. Assuming that the networks **94–100** and the networks **86–92** are identical, the system is capable of illuminating radiation patterns steered in four azimuth directions and in four elevation directions, or, in other words, it is capable of illuminating 16 directional patterns. The desired pattern is selected by delivering the transmitter signal to a selected input port of the networks **94–100**.

More specifically, similar output ports from the networks **94–100** are connected to input ports of the same network **86–92**. For example, the output ports **16—16** from the networks **94–100** are connected to the input ports of the network **86**. Correspondingly, similar input ports of the networks **86–92** are connected to the output ports from the same network **94–100**, e.g., the input ports **26—26** of the networks **86–92** are each connected to the output ports of the network **96**. This interconnection scheme permits the networks **86–92** to superimpose a second directive phase pattern onto the directive phase pattern developed by the one network **94–100** to which the input signal is delivered. The result is a choice of 16 pencil beams directed in a two-dimensional space.

Assuming a signal source is connected to the input port **32** of network **94**, the signal path through the system of FIG. 5 to each of the elements **14** is indicated with dotted lines. The signals delivered to the output ports **16**, **18**, **20** and **22** of the network **94** are phased to steer the array pattern 13° above an axis normal to the array of elements. Each of the azimuth steering networks **86–92** thus receives an input signal at the port **28** thereof having a different phase, and these networks impose a second phase gradient on the signals fed to the elements **14** to steer the beam 48° to the left of the array axis. When the networks **86–92** are identical to the networks **94–100**, the energy component radiated by each element **14** will add to generate a pattern having a single main lobe. Thus, for the example given, the lobe is tilted up by 13° and 48° to the left.

When the horizontal networks differ from each other, a plurality of beams is formed, instead of a single beam, when each input port of the vertical networks is energized.

A circular antenna system, shown in FIG. 6, capable of radiating 16 simultaneous patterns, comprises 16 four-port networks **12***a*, **12***b*, **12***c*, . . . **12***p*. Each of the four output ports **16–22** of each network **12***a*–**12***p* is connected to an antenna element **14**; the system thus has 64 antenna elements **14—14** disposed in a substantially circular array. The input ports **26–32** form four successive networks which are shown interconnected with system input ports **152**, **154**, **156**, **158** . . . to operate the four networks in parallel. Thus, 16 elements radiate simultaneously to generate each pattern.

The input ports of each four successive networks in FIG. 6 are interconnected so that the pattern generated by each network is directed toward the central radius of the four. Thus, when the system input port **152** is energized, network **12***a* is energized at its input port **30** to radiate the Two Right pattern. At the same time, networks **12***b* and **12***c* are excited at their ports **32** and **26**, respectively, to generate One Right and One Left beams. In addition, network **12***d*, excited at port **28**, radiates its Two Left pattern. These four patterns combine to form a resultant pattern oriented substantially along a radial line **160** between the **12***b* and **12***c* networks. The path of the signal from system port **152** to the 16 elements is traced with dotted lines.

In the foregoing antenna system, the signals delivered to the antenna elements **14** are substantially equal in amplitude. As stated above, when the signals delivered to an antenna array have properly tapered amplitudes, the resultant radiation pattern generally has lower side lobe levels than with a uniformly excited array. Antenna systems embodying the present invention can be readily adapted to provide antenna patterns with low side lobe levels by use of the techniques described below.

Thus, with the antenna system shown in FIG. 7, the input ports of the phasing network for adjacent beams are operated in parallel to energize the antenna elements **14** with currents whose amplitudes conform to a cosine distribution, the elements in the center of the network receiving the largest currents.

More specifically, an eight-port network **58** has eight input ports **102**, **104**, **106**, **108**, **110**, **112**, **114** and **116**. Antenna elements are connected to the output ports of this network, which has the construction shown in FIG. 2. The system has input ports **118**, **120**, **122**, **124**, **126**, **128** and **130** which are connected to a beam-combining network **131** comprising isolated power dividers or directional couplers **132—132** and couplers **134—134**. The network **131** in turn couples each port **118–130** to a pair of network **58** input ports corresponding to adjacent beams. Phase shifters **136** are connected between the dividers **132** and the couplers **134**, as shown, to adjust the phase center of one beam in each pair of adjacent beams to coincide with the phase center of the other beam in the pair. A signal delivered to the system port **118**, for example, is delivered to the *b* port of a power divider **132**, which divides the signal equally and delivers it to the couplers **134** connected to the network input ports **102** and **110**, associated with One Left and Two Left beams, respectively. The phase shifter **136** between the ports **132***d* and **102** has a fixed phase delay of 157½°, or $\frac{7}{8}\pi$ radians, to cause the two beams to add and form a resultant beam that is oriented substantially along the crossover of the One Left and the Two Left beams, respectively (FIG. 3). The phase characteristics of the other phase shifters **136** are $\frac{7}{8}\pi$ and π, as indicated in the drawing.

Still referring to FIG. 7, the power dividers **132—132** provide the desired parallel connection between two selected network input ports. Three-port dividers may be used, but four-port couplers, similar to those used in the network **58** are preferred to provide better isolation between the radiation patterns. The unused ports **132***a* are terminated with matched loads **138**.

The couplers **134—134** allow each network **58** input port to receive energy for either of the adjacent patterns, illuminated by means of the port, while retaining the desired isolation between the ports **118–130**. Thus, simultaneous, substantially cosine-illuminated patterns can be developed with the antenna system of FIG. 7, with each pattern having substantially reduced side lobe levels as compared to systems providing uniform antenna illumination. This can readily be confirmed by assuming input signals at the respective ports **118–130** and following relative phases and amplitudes through to the elements **14**, in the manner illustrated above for the networks **12**. The unused ports *c* of the couplers **134** are also terminated with matched loads **138**. The couplers **134—134** connected to the network input ports **104** and **112**, which are energized to develop the Four Right and the Four Left beams, may be omitted, since each of these beams is combined with only one adjacent beam. This decreases the number of couplers in the system and maintains a tapered illumination across the elements **14**. However, the illumination departs from a true cosine distribution, and the side lobe levels increase somewhat.

The division of signals in the couplers **134—134** between the network **58** input ports and the loads **138** imposes a 3 db insertion loss on the antenna system of FIG. 7 during transmission, and the loads **138** connected to the dividers **132** cause a similar loss during reception. However, this loss is accounted for by the tapered illumination of the resultant beams, which have a wider beamwidth and therefore less gain but lower side lobes than the original beams combined therein.

Side lobe levels of the radiation patterns may be reduced even further by energizing the antenna elements according to a cosine^2 distribution with the antenna system shown in FIG. 8, which combines sets of three successive network **58** beams. The system illustrated comprises, in addition to the eight-port network **58** and antenna elements **14**, a set of input ports **140, 142, 144, 146, 148** and **150**. Also included are two stages **137** and **139** of power dividers **132—132** and a stage of couplers **134—134**, which serve to couple three successive network **58** input ports to each of the system input ports **140–150**. Phase shifters **136—136** align the three corresponding uniformly-illuminated beams to form a single resultant cosine^2 beam. The unused ports of the power dividers **132** and couplers **134** are again terminated with matched loads **138**.

The signal path from the system input port **140** to the network input ports **114, 106** and **110** is traced with dotted lines. From this it is seen that each divider **132** in the stage **137** feeds a pair of dividers in the stage **139**. The latter dividers feed a total of three couplers **134** connected to input ports of the network **58**.

In general, the number of cosine function beams that can be formed with a network having n output ports is $n-y$, where y is the order of the cosine function. Accordingly, the antenna system has $n-y$ inputs ports. For example, the system shown in FIG. 8 has eight output ports, ($n=8$), and provides a cosine^2 antenna excitation pattern ($y=2$). Accordingly, the system has $n-y$, or 6, system input ports **140–150**.

It has been found that the dissipation losses in the beam-combining networks comprising the directional couplers **132—132** and the couplers **134—134**, as illustrated in FIGS. 4 and 8, are no greater than the losses that result when the signal delivered to each antenna element is tapered individually as in the prior art. For a $2n$ antenna system which both transmits and receives, the network provides lower losses than prior art systems. Furthermore, as the order of the cosine function increases, the losses in the beam-combining network are proportionately reduced, as compared to the losses suffered with prior art apparatus.

Referring again to FIG. 5, the side lobe levels of the radiation patterns obtained with the two dimensional antenna system may be reduced according to the principles discussed with reference to FIGS. 7 and 8. When the vertical networks **94–100** are each energized through the beam-combining networks as shown in FIGS. 7 or 8, the amplitude of the signals fed to each of the horizontal networks **86, 88, 90** and **92** is tapered and the resultant radiation pattern has reduced side lobes in its vertical plane. Similarly, the networks **86–92** may be fed through beam-combining networks. In like manner, the beam-combining networks of FIGS. 7 and 8 may be incorporated in the antenna systems of FIGS. 1*a*, 4 and 6.

In summary, we have described improved antenna systems for developing directional radiation patterns. The systems utilize four-port transmission couplers and novel circuit arrangements to provide antenna systems capable of efficient beam steering with a stationary array of antenna elements and without requiring motion of high inertia mechanical scanning systems or the like.

The antenna systems are suitable for receiving or transmitting and can easily provide illumination in a plurality of directions simultaneously, with isolation between the various beams. By utilizing modern strip line fabrication techniques, the antenna phasing networks can be constructed with a minimum cost and size. The networks require substantially fewer components than prior antenna phasing systems and they need no active circuit components.

The antenna phasing networks may be combined and constructed for antenna systems of any size and to radiate antenna patterns having substantialy any desired characteristic. Furthermore, side lobe levels are efficiently controlled by the cosine, cosine^2 systems described above.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

I claim:

1. An antenna system for radiating (n) directional antenna patterns, said system comprising in combination,
   - (A) (n) transmission networks each of which
     - (1) has a plurality of first ports and a succession of second ports, and
     - (2) provides transmission paths of different relative phase delays between each first port and all second ports thereof, said paths being so constructed as to couple a signal from each first port to all second ports with a uniform phase difference between successive second ports, said uniform phase difference being different in at least one of magnitude and sign for each first port to which a signal is applied,
   - (B) a plurality of antenna elements disposed on a substantialy circular path and connected to said second ports,
   - (C) (n) third ports and
   - (D) means interconnecting at least two of said first ports with each of said third ports so that a signal delivered to one third port is transferred to energize a plurality of said antenna elements with signal components phased so that said elements radiate a directional pattern.

2. The combination defined in claim **1** in which
   - (A) (n)=16,
   - (B) each of said networks is provided with four first ports and four second ports, and
   - (C) each third port is connected to one first port of each of four networks connected to antenna elements successively disposed along said circular array.

3. The combination defined in claim **1** in which said first ports connected to each third port are in different transmission networks.

4. The combination defined in claim **1** in which
   - (A) said first ports connected to each third port are in different transmission networks and
   - (B) each first port is connected with only one third port.

5. An antenna system for radiating (n) directional antenna patterns, said system comprising, in combination,
   - (A) (n) transmission networks each of which
     - (1) has (m) first ports and a succession of second ports, and
     - (2) provides transmission paths of different fixed relative phase delays between each first port and

all second ports thereof, said paths being so constructed as to couple a signal from each first port to all second ports with a uniform phase difference between successive second ports, said uniform phase difference being different in at least one of magnitude and sign for each first port to which a signal is applied,

(B) a plurality of antenna elements disposed on a substantially circular path and connected to said second ports,

(C) (n) third ports each of which is associated with one first port of a group of (m) transmission networks, and

(D) transmission means

(1) interconnecting each third port with said group of (m) first ports associated therewith so that a signal delivered to one third port is transferred to energize said antenna elements connected to said (m) associated transmission networks with signal components phased so that said elements radiate one of said directional patterns,

(2) coupling signals developed at a group of (m) first ports in response to energy received in one of said directional patterns to the associated third port substantially in phase with each other.

6. An antenna system for radiating directional antenna patterns having low side lobe levels, said system comprising, in combination,

(A) antenna elements,

(B) a radio frequency circuit having a plurality of first ports and a succession of second ports coupled to said antenna elements, transmission paths of different relative phase delays between each of said first ports and all of said second ports, said paths being so constructed as to couple a signal from any given first port equally to each second port with a uniform phase difference between successive second ports, so that said antenna elements radiate different spaced beams when a signal is applied to different first ports, said transmission paths including four-port couplers cross-connecting said paths and isolating said first ports from each other and said second ports from each other,

(C) a plurality of third ports, and

(D) transmission means

(1) interconnecting said first ports with said third ports so that at least two first ports are energized when a signal is delivered to one of said third ports, and

(2) adapted to impart a phase difference between the signal components delivered to said energized first ports so that said antenna elements have a substantially common phase center.

7. An antenna system for radiating directional antenna patterns, said system comprising, in combination,

(A) a plurality of antenna elements,

(B) a radio frequency beam-forming network having a plurality of first ports and a succession of second ports coupled to said antenna elements and transmission line paths of different fixed relative phase delays between each of said first ports and all of said second ports so as to couple a signal from each first port equally to every second port with a uniform phase difference between successive second ports whereby said antenna elements radiate different spaced beams when a signal is applied to different first ports, said beam-forming network isolating said first ports from each other and said second ports from each other,

(C) a plurality of third ports, and

(D) transmission means

(1) interconnecting said first ports with said third ports so that at least two first ports are energized when a signal is delivered to one of said third ports,

(2) arranged to impart a phase difference between the signal components delivered to said energized first ports so that said beams radiated by said antenna elements have a substantially common phase center, and

(3) arranged to energize said first ports with signals having selected relative amplitudes in response to a signal applied to the third port connected to the first ports.

8. An antenna system according to claim **7** in which said transmission means interconnects each third port with first ports that couple signals to said second ports with successively greater phase differences.

9. An antenna system according to claim **7** in which said transmission means interconnects each of at least a plurality of first ports with two third ports.

10. An antenna system according to claim **7** in which said transmission means includes

(A) a plurality of first couplers each of which has one port connected to one first port and at least two further ports coupled with said one port thereof, and

(B) a plurality of second couplers each of which has one port connected to one third port and at least two further ports coupled with said one port thereof.

11. An antenna system according to claim **10** in which said two further ports of each of said first and second couplers are substantially isolated from each other.

12. An antenna system for radiating ($n-y$) directional patterns, said system comprising in combination

(A) (n) uniformly spaced antenna elements,

(B) a transmission network

(1) having (n) first ports,

(2) having a succession of (n) second ports, each of which is connected to a different one of said antenna elements,

(3) having $n/2\ \log_2 n$) four-port directional couplers arranged in (m) successive stages, where $2^m=n$,

(a) each stage having substantially the same number of couplers,

(b) each of said couplers in a last stage thereof immediately adjacent to said second ports being connected to second ports spaced ($n/2$) second ports apart,

(4) two first ports being connected to two ports of each of said couplers in a first stage of couplers immediately adjacent to said first ports,

(5) whereby said network provides transmission line paths of different fixed relative phase delays between each of said first ports and all of said second ports, said paths being so constructed as to couple a signal from any first port equally to each second port with a uniform phase difference between successive second ports so that a different antenna beam is generated when a signal is fed to each of said first ports,

(C) ($n-y$) third ports where (y) is the order of a cosine function according to which the amplitudes of signals delivered to said second ports from each of said third ports are distributed, and

(D) means interconnecting said first ports with said third ports to simultaneously energize ($y+1$) first ports when a signal is delivered to a third port,

(1) the first ports that are so energized being associated with spatially successive beams,

(2) said interconnecting means being adapted to cause said successive beams to substantially coincide and form a single resultant beam,

(3) said interconnecting means being arranged to deliver, from each third port to said first ports energized from it, signals having amplitudes that produce a $(\text{cosine})^y$ illumination of the second ports.

13. The combination defined in claim 12 in which
(A) $(y)=1$ and
(B) said interconnecting means comprises
(1) a stage of second directional couplers each of which has a port connected to one first port,
(2) $(n-1)$ third directional couplers, each of which has a first terminal connected to one of said third ports, and
(3) transmission means connecting second and third terminals of each of said third couplers to the second couplers connected to a pair of first ports that are simultaneously energized, said transmission means having phase delays which cause the phase centers of the adjacent beams that are generated simultaneously to substantially coincide.

14. The combination defined in claim 12 in which
(A) $(y)=2$ and
(B) said interconnecting means comprises
(1) a stage of second directional couplers, each of which has a port connected to one first port,
(2) $(n-2)$ third directional couplers, each of which has a first terminal connected to one of said third ports, and
(3) transmission means connecting second and third terminals of each of said third couplers to the second couplers connected to three said first ports that are simultaneously energized, said transmission means including relative phase delays and a stage of fourth directional couplers arranged to cause the phase centers of the adjacent beams that are generated simultaneously to substantially coincide.

15. An antenna system for radiating directional patterns, said system comprising in combination
(A) a plurality of uniformly spaced antenna elements,
(B) a transmission network
(1) having plural first ports ordered in a first sequence,
(2) having a succession of second ports each of which is connected to a different antenna element,
(3) having means forming first transmission paths of different electrical lengths from each first port to all the second ports thereof, said first paths coupling a signal from each first port to all the second ports thereof with a uniform phase difference between successive second ports, said uniform phase difference being different for each first port to which a signal is applied, and
(4) energizing said antenna elements to produce different consecutively spaced radiation beams when a signal is successively applied to different first ports according to said first sequence,
(C) a plurality of third ports, each third port being associated with a group of at least two first ports successively arranged in said first sequence, and
(D) transmission means connected between said third ports and said first ports and simultaneously energizing all said first ports in a group thereof when the associated third port is energized.

16. An antenna system according to claim 15 for forming $(n-y)$ directional patterns and having
(1) (n) antenna elements,
(2) (n) first ports,
(3) (n) second ports,
(4) $(n-y)$ third ports, and
(5) $(y+1)$ first ports in each group thereof associated with one third port.

17. An antenna system according to claim 15 wherein said transmission means
(A) form between each third port and said first ports associated therewith, second transmission paths having different electrical lengths so as to cause the beams produced by energizing a third port to have a substantially common phase center, and
(B) energize the first ports in each group thereof, when the associated third port is energized, with signals having selected relative amplitudes.

References Cited by the Examiner

UNITED STATES PATENTS

3,135,917	6/1964	Best et al.	
3,222,677	12/1965	Fink	343—100.6
3,255,450	6/1966	Butler	343—100.6

CHESTER L. JUSTUS, *Primary Examiner.*

H. C. WAMSLEY, *Assistant Examiner.*