United States Patent [19]

Connolly

[11] **3,906,502**

[45] **Sept. 16, 1975**

[54] **BILATERAL SERIES FEED FOR ARRAY ANTENNAS**

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[73] Assignee: **General Electric Company,** Syracuse, N.Y.

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[52] **U.S. Cl.**..... **343/100 SA;** 343/853; 343/854

[51] **Int. Cl.**[2]..... **G01S 3/74**

[58] **Field of Search**..... 343/100 SA, 854, 853

[56] **References Cited**

UNITED STATES PATENTS

3,295,134	12/1966	Lowe	343/100 SA
3,509,577	4/1970	Kinsey	343/854

Primary Examiner—Maynard R. Wilbur
Assistant Examiner—Richard E. Berger
Attorney, Agent, or Firm—Carl W. Baker; Joseph B. Forman; Frank L. Neuhauser

[57] **ABSTRACT**

A bidirectional array antenna system is disclosed, of series feed type, which provides two differently directed arrays each capable of forming and steering transmit and receive beams through an angular sector, and which requires but a single set of elemental phase shifters and drivers for forming and steering the two beams. This is accomplished by bilateral use of the elemental phase shifters in the beamforming operations of both arrays while maintaining isolation between arrays by use of the characteristic orthogonality of series feeds to wave energy with phase gradients unmatched to the feed. The two beams may be thus formed and steered either simultaneously or in time alternation, through the angular sectors for which the respective arrays are oriented.

7 Claims, 6 Drawing Figures

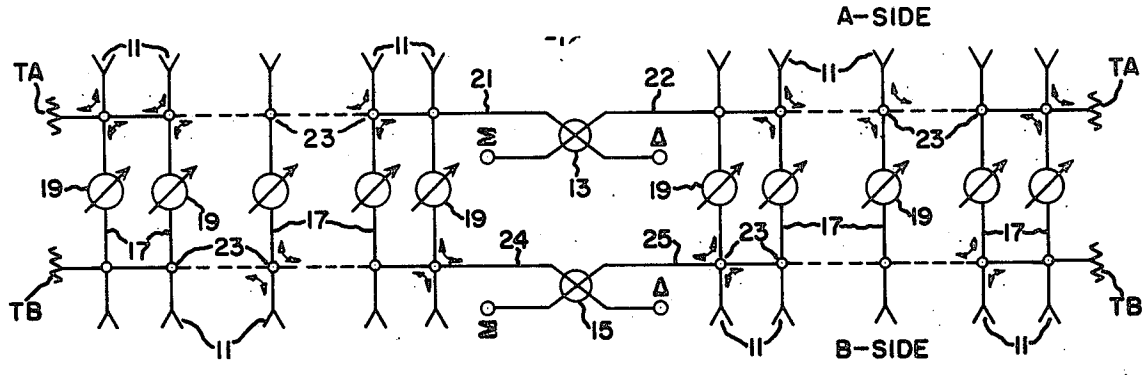


FIG.1

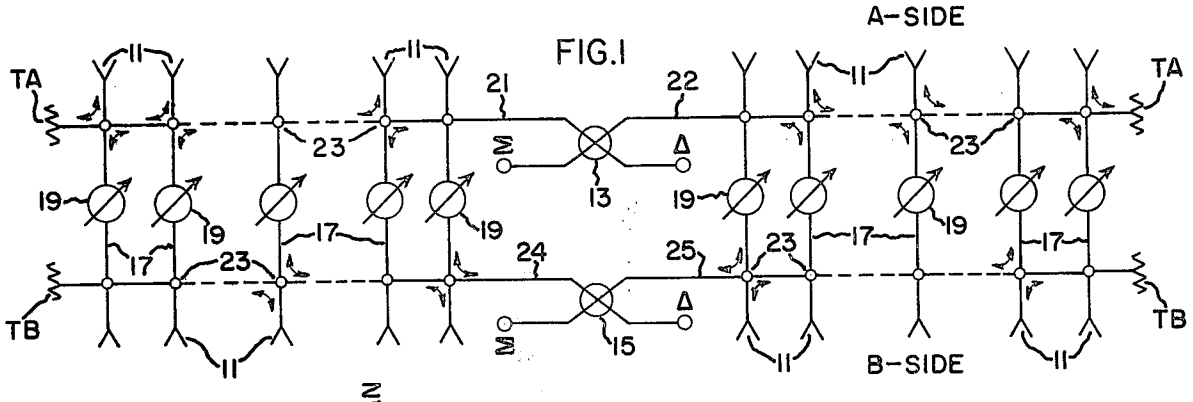


FIG.2

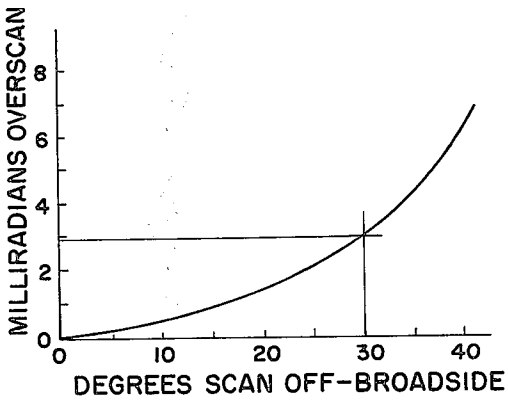


FIG.3

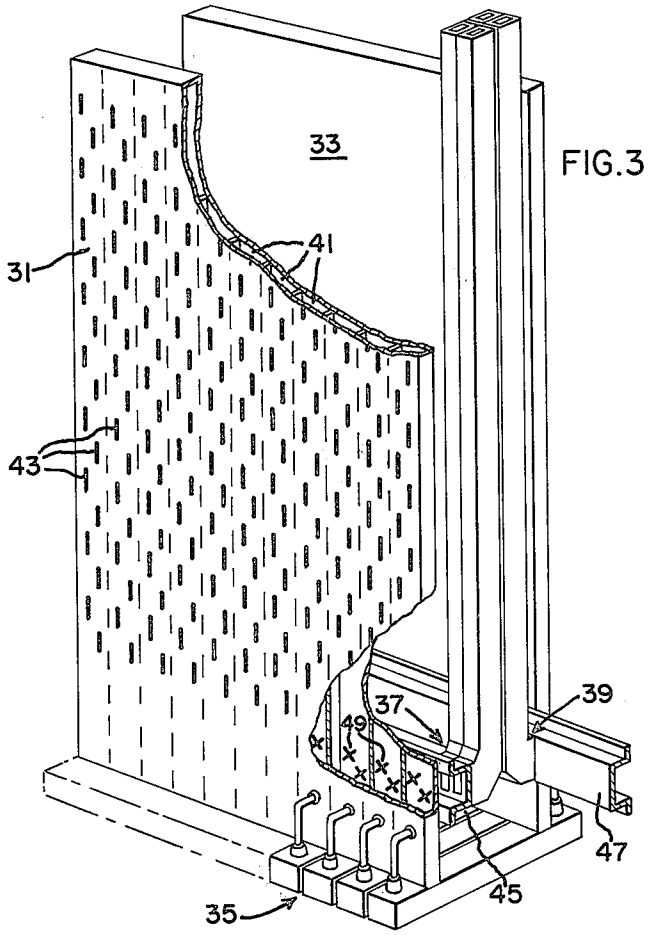
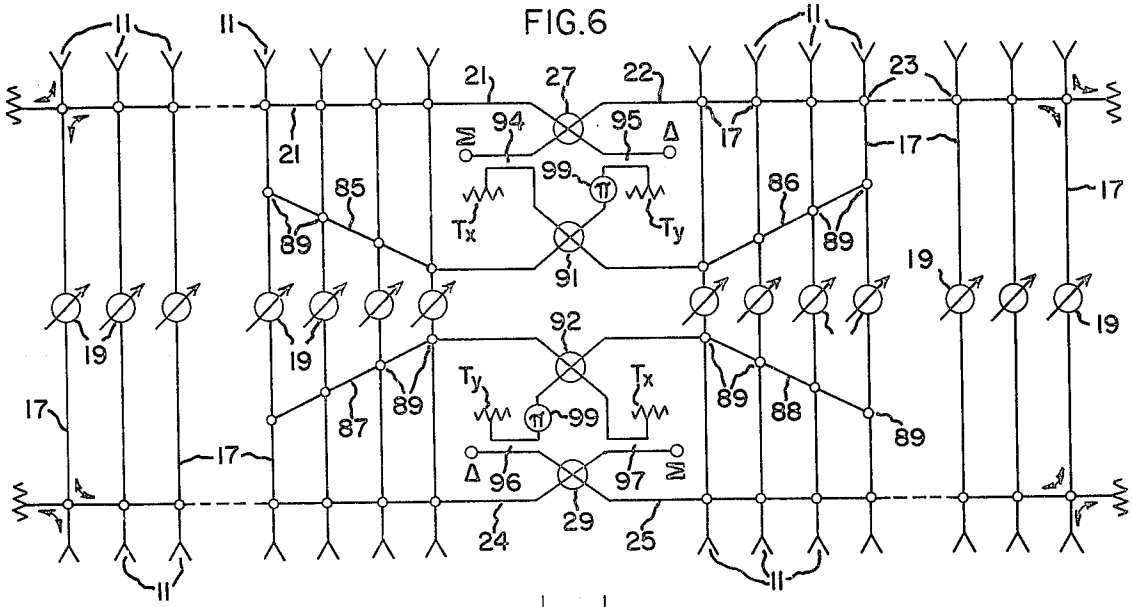


FIG.6



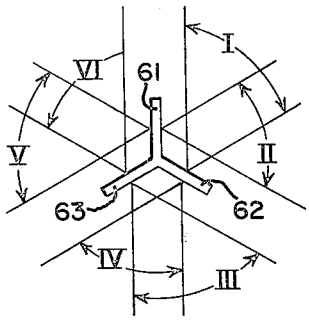
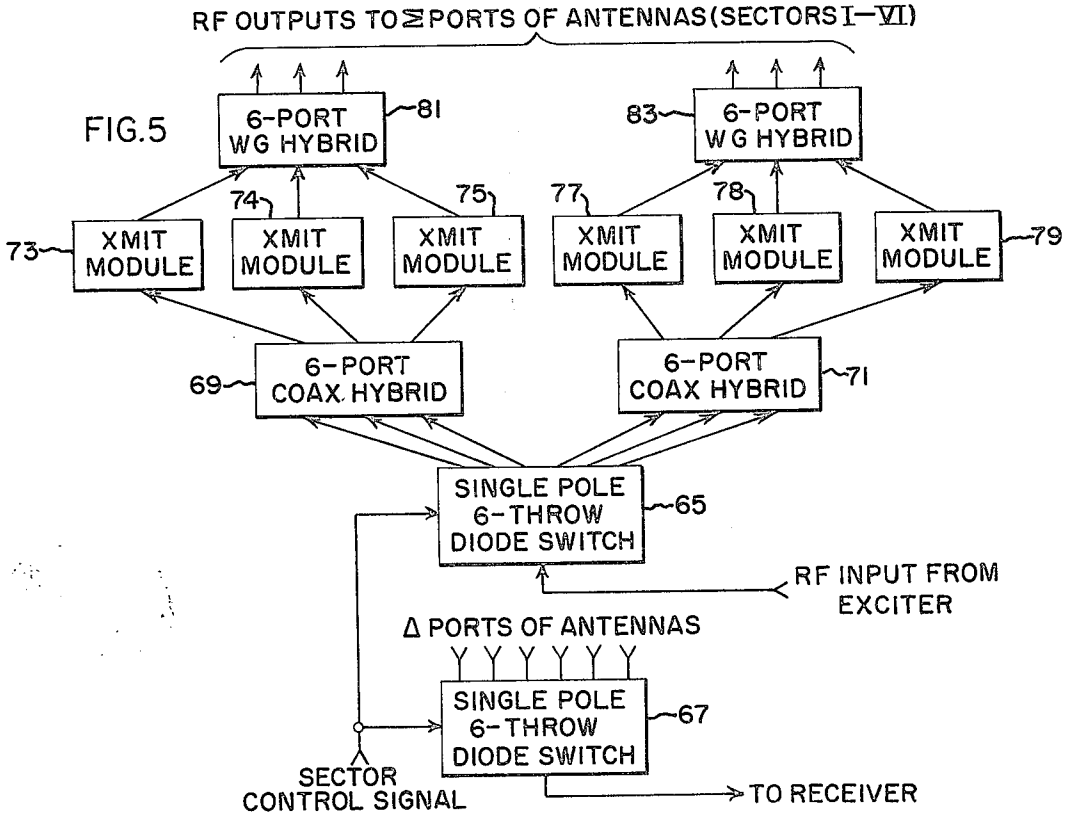


FIG.4

FIG.5



BILATERAL SERIES FEED FOR ARRAY ANTENNAS

BACKGROUND OF THE INVENTION

The present invention relates generally to radar antenna arrays and feed systems therefor. More particularly it relates to a bidirectional array which is capable of forming two independent beams either simultaneously or in time alternation and electronically steering the two beams through different angular sectors, and which provides such bidirectional beam forming capability with substantial reduction in complexity and cost as compared against conventional arrays.

Multidirectional electronically scanned antenna systems have heretofore been proposed, recent examples of such proposals being described in U.S. Pat. Nos. 3,295,134 to Lowe, 3,430,242 to Safran and 3,648,284 to Dax et al. Apart from their common capability to form a number of beams each capable of scanning a different angular sector, however, these prior art proposals have little in common either with each other or with the bilateral series feed array of the present invention, which in its simplest and presently preferred form permits scanning of bidirectional beams formed by two differently directed array faces, using only one set of phase shifters for both beams. The invention may be applied to both phase-phase and phase-frequency scanned arrays, and in either embodiment the bilateral series feed may take the form of back-to-back linear arrays which are relatively simple and low cost both as to array structure and to associated control circuitry. By provision of a plurality of such arrays arranged in any of several different configurations it is possible to obtain complete azimuthal coverage in a relatively compact structure easily transportable if desired.

The basic series-feed array is described in U.S. Pat. No. 3,258,774 to Richard R. Kinsey, assigned to the assignee of the present invention. Such an array comprises a series feed or main transmission line with directional couplers spaced along the line for coupling wave energy to and from it and a number of branch feed lines each containing a phase shifter and each terminated by one of the radiation elements of the array. Typically the feed and transmission lines both are waveguide and the directional couplers are cross-guide couplers, with the coupling coefficients of the individual couplers being selected to shape the resultant beam as desired. While not essential to the concept, series feed arrays commonly are divided into two subarrays center-fed by a 3db hybrid, and normally the branch feed line ends remote from the radiation elements are terminated in matched impedances to improve element-to-element isolation and minimize perturbations due to the finite directivity of the couplers. A number of modifications and improvements to the basic series feed concept have been proposed and most of these, such for example as the tandem series feed system described in another patent of Richard R. Kinsey, U.S. Pat. No. 3,509,577, may advantageously be utilized in the bilateral series feed systems of the present invention as detailed hereinafter.

SUMMARY OF THE INVENTION

The present invention has as its primary objective the provision of bilateral phased arrays capable of scanning two angular sectors, either simultaneously or in time alternating fashion, using but a single set of phase shifters and drivers to control beam formation and beam steering through both angular sectors. In accordance with the invention such dualsector coverage may be provided without need for two complete arrays, by bilateral use of the array phase shifters and by utilization of the orthogonality of the array feeds to energy which is not phase matched thereto, to provide adequate isolation between the array faces notwithstanding their shared use of feed elements. The invention may be implemented as a bidirectional phase-scanned line array or as a bidirectional planar array for phase-phase or phase-frequency scan as preferred.

Briefly stated, one presently preferred embodiment of the invention as applied to a phased array radar utilizes a plurality of radiation elements arranged in paired relation with the two elements of each pair interconnected through elemental or branch feed lines each of which includes a centrally located phase shifter adjustable for phase control. Each branch feed line is intercoupled with both of two series feed or main transmission lines at points spaced along them, by directional couplers connected into the feed lines on either side of the phase shifters. Suitable transmit-receive means are connected, preferably through hybrid junctions, to the ends of the main transmission lines for series feed therethrough to the branch lines. Due to the orthogonality of the series feed to wave energy not phase-matched thereto, energy applied to either of the series feed lines through its associated input-output hybrid junction will couple unidirectionally into the branch lines, through the phase shifters therein, and to the radiation elements on the side of the array remote from the series feed line on the input side. Conversely, energy applied to the other series feed line will be routed in the opposite direction through the phase shifters and to the radiation elements comprising the opposite face of the array. The phase shifters will in either case determine the phase relations of the signals as passed to and from their respective radiation elements, and thus control the beams formed and steered thereby. With reciprocal phase shifters the two beams thus formed may be scanned simultaneously; with nonreciprocal phase shifters the beams may be time multiplexed with appropriate readjustment of phase shifter settings between successive pulse intervals.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be further understood by reference to the following detailed description when read in conjunction with the accompanying drawings, wherein:

FIG. 1 is a block diagram of a phased array radar system providing bidirectional capability in accordance with the invention;

FIG. 2 illustrates an operational characteristic of the array feed of FIG. 1;

FIG. 3 is a part-sectional perspective of an array antenna and feed structure representing one implementation of the invention of FIG. 1;

FIG. 4 illustrates schematically an arrangement providing 360° coverage using three of the bidirectional beam arrays of FIG. 1;

FIG. 5 is a block diagram of transmit-receive means suitable for use with the 360° coverage array of FIG. 4; and

FIG. 6 is a block diagram of a modified form of the invention utilizing tandem series feed for the array.

DESCRIPTION OF PREFERRED EMBODIMENT

The invention is illustrated in FIG. 1 as embodied in a phased array radar of center-fed series feed type. The array comprises a plurality of radiation elements **11** arranged in paired relation to form two differently directed arrays, designated the A-side and B-side arrays in FIG. **1.** Each of these arrays is divided into two subarrays, with center feed means comprising one of two hybrid junctions **13** and **15** located between the left and right subarrays on the A-side and B-side, respectively.

The two radiation elements **11** of each pair are connected to opposite ends of branch feed lines **17** and constitute the terminations therefor on their respective sides of the array. Centrally disposed with respect to each of the branch feed lines **17** is a variable phase shifter **19** which operates on signals transmitted through the branch feed line to impart differing phase shifts each of magnitude determined by a control signal applied to the respective phase shifter by a steering command signal source (not shown). These phase shifters **19** may be either analog or digital and either reciprocal or nonreciprocal in operation; by way of example one suitable design may be found in U.S. Pat. No. **3,290,622** to Hair.

Each of the branch feed lines **17,** at a point between the associated phase shifter **19** and the radiation element **11** on that side of the array, connects through a cross guide coupler **23** to one of two series feed or main transmission lines **21-22** and **24-25** on the array A-side and B-side, respectively, these series feed lines being provided with terminations TA and TB as shown for matching purposes. The cross guide couplers **23** through which these connections are accomplished may desirably have coupling slot configurations such as described in detail in U.S. Pat. Nos. **3,230,483** and **3,377,571,** both issued to Kinsey.

The two 3db terminals of hybrid junction **13** connect to the two halves of the A-side of the antenna array, and the sum and difference terminals of the junction, designated Σ and Δ respectively, connect to the associated transmit-receive means (not shown). Such transmit-receive means normally comprise a transmitter and a sum receiver connecting through suitable duplexer or TR switch means to the sum terminal, and a difference receiver connected to the difference terminal. The two halves of the B-side array are similarly coupled through hybrid junction **15** to transmit-receive means (not shown) which may be separate from the A-side transmit-receive units or the same units may be time-shared to support both A-side and B-side operation.

In operation of the bilateral array of FIG. **1,** radio frequency energy introduced at the sum terminal of hybrid junction **13** to the A-side series feed is divided thereby with half the energy propagating along each of the two series feed lines **21** and **22** on the A-side of the array. At each of the cross-guide couplers **23,** a predetermined fraction of this energy is tapped off and coupled unidirectionally into the associated branch feed line **17,** toward the phase shifter **19** therein, and therethrough to the directional coupler **23** in the same branch line but on the B-side of the array. Here the operation of the coupler **23** is such that substantially all the energy is directly passed to the B-side radiation element which terminates the associated branch feed line, and is radiated thereby.

The direction of the radiant energy beam thus formed by the B-side radiation elements is determined by the settings of the phase shifters **19,** under the control of appropriate computing elements (not shown) which determine the proper setting for each of the phase shifters for any desired beam position and provide appropriate signals, either mechanical or electrical, to adjust the phase shifters accordingly. The width and shape of the radiated beam are determined by the amplitude taper of the wave energy applied to the several radiation elements **11** on the B-side, which in turn is determined by the coupling characteristics of the directional couplers **23** on the input side of the array, i.e., those on the A-side in this instance.

During operation with power input to the A-side, the high directivity of the couplers **23,** which typically may provide of the order of **30**db of directivity, will permit of only little loss of energy by radiation from the A-side of the array. At the same time, relatively little energy will be lost by coupling into the B-side series feed line **24-25** under these conditions, provided that the beam is not scanned beyond a definite and predetermined limit. This scanning limit is a function of the feed design and occurs when the elemental phase gradient, as determined by the settings of the phase shifters **19,** reaches a point of correspondence with the electrical spacing between the couplers **23** in these series feed lines **24** and **25.** If this limit is reached, wave energy input from the A-side feed line **21-22** transmitted through couplers **23** then may combine coherently in the other feed line **24-25** and appear as output at the terminals of the B-side hybrid junction **15** at the center point of that line. For practical feed designs, however, scan sectors up to **75°** or **80°** can be accommodated without such interfeed coupling exceeding **—20**db, so this limitation presents no serious problem in most installations and particularly not in those in which coverage of an angular sector of **60°** is desired, as for example in the system of FIG. **5** described hereinafter.

One additional result of such recoupling of wave energy in the second feed line **24-25** is a slight perturbation of the radiated wave front. This results from the fact that some part of the energy which does couple into feed line **24-25** and propagates along the same toward its center, will be redirected by the next inner directional coupler **23** into its associated branch line **17** toward the B-side radiation element **11** terminating that line, thus adding to the direct-path wave energy which is transmitted to that element through its own branch line coupler. Toward the center of the array, there will be a plurality of such recoupled waves adding to and reinforcing the direct-path waves at the respective radiators.

Normally such perturbing waves are distributed in phase with respect to one another and so do not sum to any appreciable amplitude, but as the array is scanned toward the extremes on either side of the covered angular sector these perturbing waves begin to approach phase coherency and thus have a greater affect on the amplitude and phase of the individual radiator excitations. The effect is a progressive overscan as that extreme is approached; as the beam is scanned toward the opposite extreme there is a similar but opposite overscan effect. The degree of such overscan is a known function of array scan angle and can, therefore, easily be compensated for in calibrating beam pointing direction. FIG. **2** illustrates this overscan for one half

of the network, as a function of beam scan angle off broadside, and as will be obvious from this figure the relatively small magnitudes of overscan angle and the relatively simple relationship thereof to the beam look angle enables ready correction by compensation in the associated read-out circuitry.

Referring again to FIG. 1, operation of the array shown is the same as just described when wave energy is applied to the B-side input hybrid junction 15, but now of course the beam will be formed by the A-side radiation elements, at an angle with respect to the plane thereof which is again dependent upon the settings of the phase shifters 19. If these phase shifters are reciprocal in operation, the two beams formed by the A-side and B-side arrays may be formed simultaneously; if the phase shifters are nonreciprocal in operation then the two beams preferably are formed in time alternation with the phase shifters 19 being adjusted between energizations of the A-side and B-side arrays as necessary to obtain the desired look angle for each side. Similarly, again depending on whether the phase shifters are reciprocal, phase shifter reset may be necessary between the transmit and receive operations of each array. Conventional duplexing or transmit-receive devices and techniques may be used in switching between transmit and receive operations of the arrays. Alternatively, the arrays may if preferred be self-duplexed as described in U.S. Pat. No. 3,380,053 to the present inventor, in which case the receivers would be directly connected to the difference ports of the center feed junctions.

As will be obvious to those skilled in the art, the two array faces comprising the A-side and B-side radiation elements may be oriented in parallel relation as shown, or they may be disposed at an angle with respect to each other with appropriate cabling and phase corrections of the phase shifters 19 so as to preserve the necessary phase relationships at the associated directional couplers. Bidirectional arrays in accordance with the invention may be of simple line configuration for one-dimensional scan as in FIG. 1, or a plurality of such line arrays may be stacked to form a planar array of phase-phase scanned type. A single line in accordance with the invention may also be combined with linear radiators to form a planar array of the phase-frequency scanned type. Various combinations of these configurations may also be made for limited scan or combined phase and frequency scan in one or both dimensions.

FIG. 3 illustrates one possible implementation of such phase-frequency scanned planar array. FIG. 3 shows the left-hand of a bidirectional array assembly comprising back-to-back array face half-panels 31 and 33, a plurality of phase shifters designated generally by reference numeral 35, and a pair of hybrid junction assemblies designated generally by reference numerals 37 and 39. The Σ and Δ terminals of these junctions provide external connection to the array, and the two 3db terminals of each connect to the array right and left half-assemblies only one of which is shown. Each array face half-panel 31-33 consists of a plurality of vertically oriented and contiguous waveguides 41, each containing radiating slots 43 along all but the lowermost portions thereof as shown. Preferably these slotted panel surfaces are covered with a thin dielectric sheet (not shown) to provide an environmental seal for the waveguide.

The feed system is located at the bottom of the array, at which the lower ends of paired waveguides 41 on opposite sides of the array connect through the phase shifters 35 to form branch line feeds corresponding to the branch lines 17 of FIG. 1, except that here the branch feed lines are terminated at each end with a slotted guide linear radiator rather than with a simple dipole as in FIG. 1. The two series feed lines for the left half-assembly are shown at 45 and 47, running horizontally along the inner surface of each of the two face panels 31 and 33. These lines are coupled to hybrid junctions 37 and 39 at the center of the array, and are coupled into the vertical waveguides 41 which form the branch feed lines through slot-type directional couplers 49, with two slots per coupler and with the slots preferably configured in accordance with teachings of the aforementioned patents to Kinsey.

RF energy is coupled to and from the associated transmit-receive equipments by way of the hybrid junctions 37 and 39, which divide the power equally between the left and right half-array series feed lines for propagation outwardly through those lines and coupling through slot couplers 49 into the waveguides 41. Energy thus tapped off into each of the vertical waveguides 41 passes then through the associated phase shifter 35 to the corresponding vertical guide in the other face panel; it then propagates upwardly through this guide, past the series feed connection thereto, and is coupled to space through the face radiating slots 43.

The beam thus formed may be scanned in elevation by variation of the frequency of the applied RF energy, and scanned in azimuth by adjustment of the settings of the phase shifters 35 as previously explained. Preferably, each vertical waveguide contains small terminations (not shown) at its opposite ends, and the waveguides may be provided with ridges, also not shown, on their back walls to decrease their cutoff frequency. This allows frequency scan with slot spacings significantly smaller than one free-space wavelength over the entire operating band, and serves also to concentrate energy near the center of the guide, which permits less lateral staggering between adjacent slots and larger values of slot conductance.

As explained in reference to FIG. 1, the bidirectional array assembly of FIG. 3 may by proper selection of the phase shifters 35 be operated to provide either simultaneous or sequential scan through the angular sectors through which scan coverage is provided by its opposite faces. To obtain coverage through a full 360° azimuthal angle, three array assemblies may be grouped as shown in FIG. 4, with the arrays 61, 62 and 63 oriented at angles of 120° with respect to each other. Then each face of the array will provide coverage of one of the six 60° angular sectors designated I–VI, respectively, for total coverage of 360°. This arrangement enables all the arrays to be mounted in the same plane and their geometric disposition places the projected aperture of each array outside those of the others for all angles of scan within the 60° allotted sectors.

FIG. 5 illustrates multiplexer circuitry suitable for providing interconnection of the 360° scan system of FIG. 4 with its associated transmit-receive elements. As illustrated, this multiplexer comprises two diode switches 65 and 67 for selecting the desired one of six array faces for transmission and reception, respectively. For reception, switch 67 directly connects to the receiver (not shown) the appropriate difference (Δ)

port of one of the six hybrid junctions associated with the three bidirectional arrays. For transmission, the other switch **65** transfers exciter power to one of two six-port coaxial hybrids, a left-hand face hybrid **69** and a right-hand face hybrid **71.** The sector control input selects one of these hybrids in accordance with whether the left or right array face is to be activated, and applies exciter power to one of the three input ports of that hybrid. The hybrid divides this power equally between its three output ports but with different phase relationships between the three outputs uniquely determined by the input port which was selected.

Each of the outputs of the six port waveguide hybrids is connected to an input of one of the three transmitter modules **73-75** or **77-79.** The outputs of these modules are combined in another six-port waveguide hybrid **81** or **83,** and the outputs of these hybrids applied to the sum ports of the antenna arrays. In this way the multiplexer circuitry of FIG. **5** enables energization of the six faces of the array, one face at a time, in predetermined sequence determined by the sector control signal control input, to provide either continuous scan or point-to-point steering as preferred. In either case, within the angular sector covered by the energized array face, control of the beam is responsive to the settings of the associated phase shifters which also provide self-duplexing in the manner previously explained.

As already mentioned, it is possible to combine with the bilateral series feed of the present invention the tandem series feed of the aforesaid Kinsey U.S. Pat. No. **3,509,577.** This combination, which is illustrated in FIG. **6,** enables the same independence of excitation of the sum and difference mode of operation of each half of the bilateral array as described in the Kinsey patent for the basic tandem series feed.

The provision of such tandem series feed capability requires only the addition of another series feed line paralleling each of the feed lines **21–25** as shown at **85–88,** with cross-guide coupling through directional couplers **89** to at least some of the branch feed lines **17** as illustrated. These additional series feed lines are connected through 3db hybrid couplers **91** and **92** having their sum and difference ports connected to signal couplers **94–97** which are of the kind and operate in the manner fully explained in the aforesaid Kinsey patent. Phase shifters **99** are interposed in the connections between the difference ports of these couplers and impedance matching terminations Tx and Ty may be provided as shown.

As described in the Kinsey patent, substantially complete independence of sum and difference excitation modes may be achieved for both sides of the bilateral array by proper slope or tilt of the tandem feed lines **85–89** or, in lieu of such sloped feed line arrangement, the phase relationships necessary to independence of sum and difference excitations may be accomplished by interposing fixed phase shift elements in each of the branch feed lines so as to provide the desired phasing therein.

While in this description of the invention only certain presently preferred embodiments have been illustrated and described by way of example, many modifications will occur to those skilled in the art and it therefore should be understood that the appended claims are intended to cover all such modifications as fall within the true spirit and scope of the invention.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. In combination in a phased array radiator system providing bidirectional first and second wave energy beams,

a. a plurality of radiation elements arranged in paired relation with the first elements of said pairs together constituting a first ordered array for forming said first beam and with the second elements of said pairs constituting a second ordered array for forming said second beam,

b. a plurality of branch feed lines one being connected between the two elements of each of said radiation element pairs,

c. a plurality of phase shift means one being interposed in each of said branch feed lines to control independently the phase of wave energy passed therethrough,

d. first and second transmission lines,

e. a plurality of directional coupling means spaced along each of said transmission lines, with the coupling means associated with said first transmission line intercoupling that line with each of said branch feed lines at points therein between said phase shift means and said second radiation elements, and with the coupling means associated with said second transmission line intercoupling that line and each of said branch feed lines at points therein between said phase shift means and said first radiation elements, and

f. transmit-receive means and means for coupling said transmission lines thereto for providing thereto or therefrom signals representative of the two wave energy beams respectively formed by said first and said second ordered arrays.

2. A phased array radiator system as defined in claim **1** wherein said phase shift means are adjustable to variably control the phase of wave energy passed therethrough, to thereby provide control of the direction of each of said first and second wave energy beams.

3. A phased array radiator system as defined in claim **2** wherein the spacing of said directional coupling means along their respective transmission lines is such that wave energy applied through one of said transmission lines is orthogonally phased with respect to the other of said transmission lines, whereby said first and second beams may be steered through a sector of substantial angular width with relatively small coupling between the two transmission lines.

4. A phased array radiator system as defined in claim **2** wherein said phase shift means are reciprocal in operation whereby said first and second beams may be formed simultaneously.

5. A phased array radiator system as defined in claim **2** wherein said phase shift means are non-reciprocal in operation and said first and second beams are formed in time alternation.

6. A phased array radiator system as defined in claim **1** further including third and fourth transmission lines and directional coupling means intercoupling said third and fourth transmission lines with at least some of said branch feed lines at points between said phase shift means and said first and second transmission lines, respectively.

7. For providing **360°** coverage, an assemblage of three of the phased array radiator systems of claim **1** oriented at angles of **120°** with respect to each other so as to place the projected aperture of each of the six beams formed thereby outside those of the others within their respective **60°** sectors.

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