Nov. 21, 1967 K. S. KELLEHER 3,354,461

STEERABLE ANTENNA ARRAY

Filed Nov. 15, 1963 3 Sheets-Sheet 1

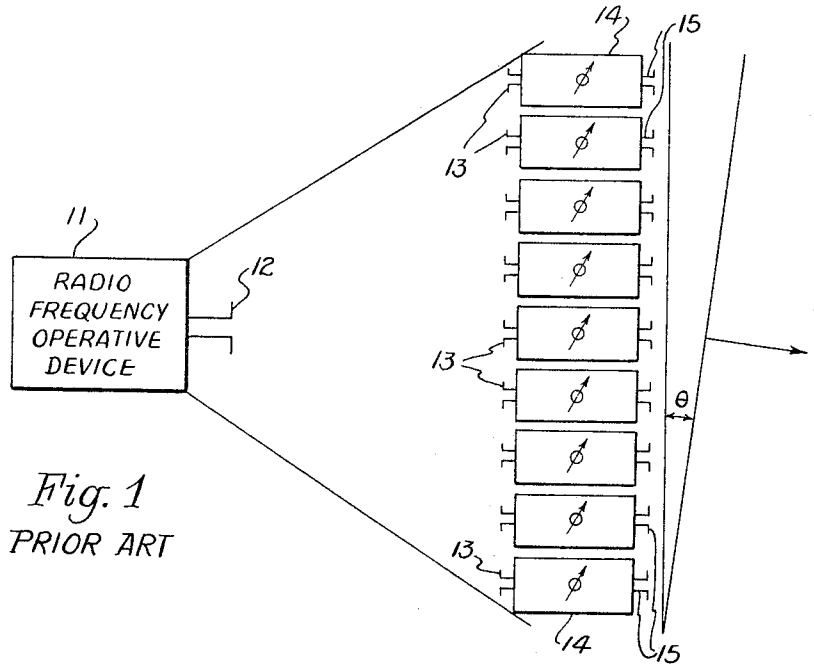


Fig. 1
PRIOR ART

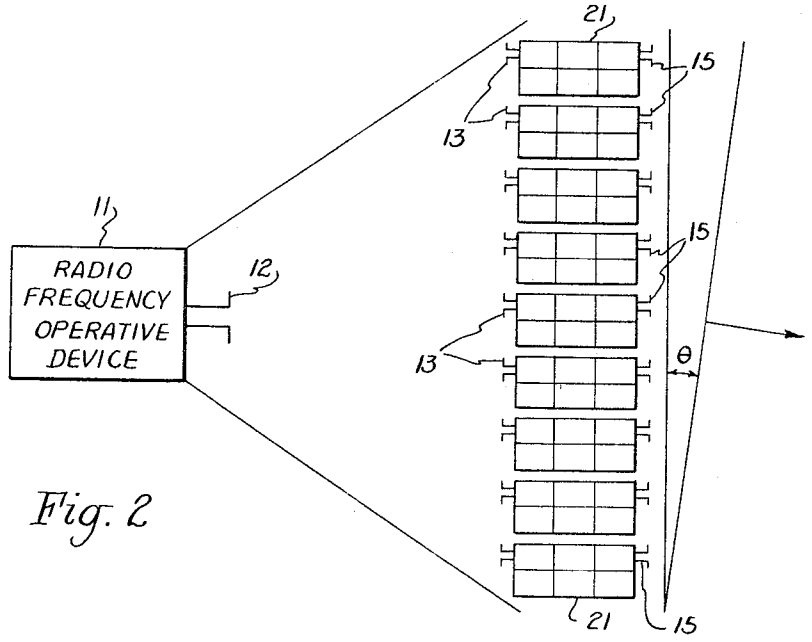


Fig. 2

INVENTOR

Kenneth S. Kelleher

BY Glenn S. Orvick

AGENT

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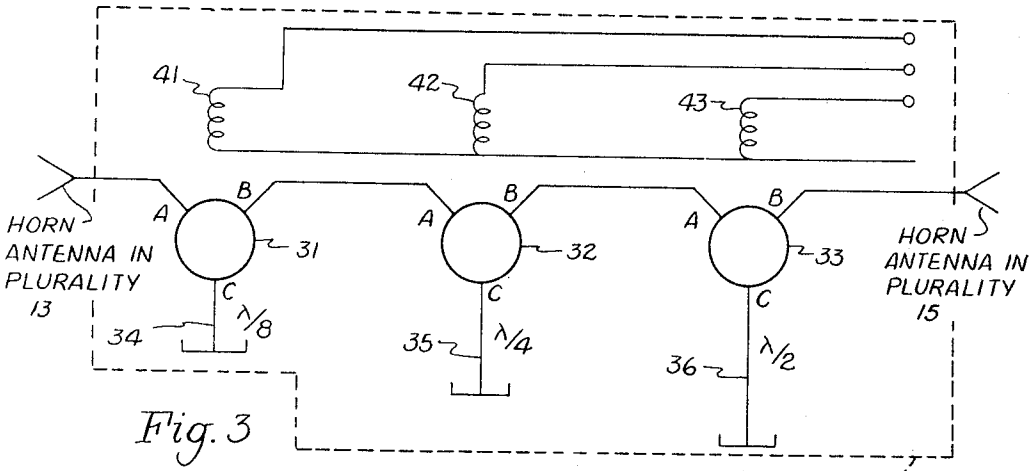


Fig. 3

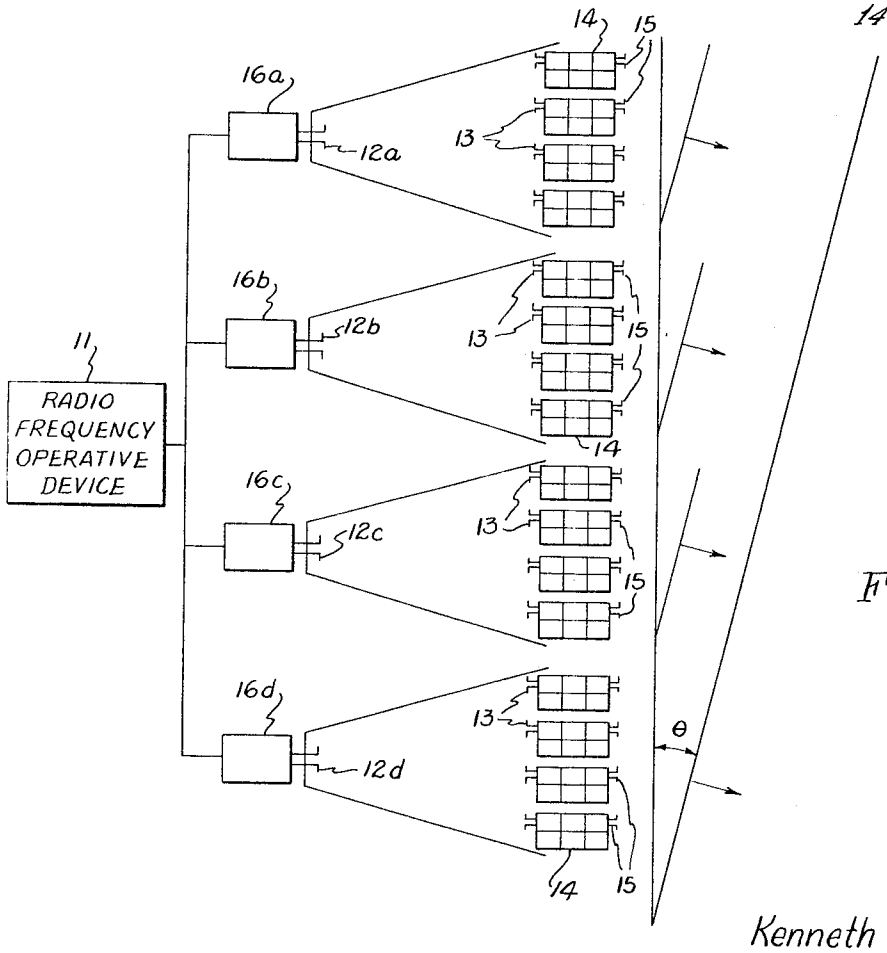


Fig. 6

INVENTOR

Kenneth S. Kelleher

BY Glenn S. Arvesik

AGENT

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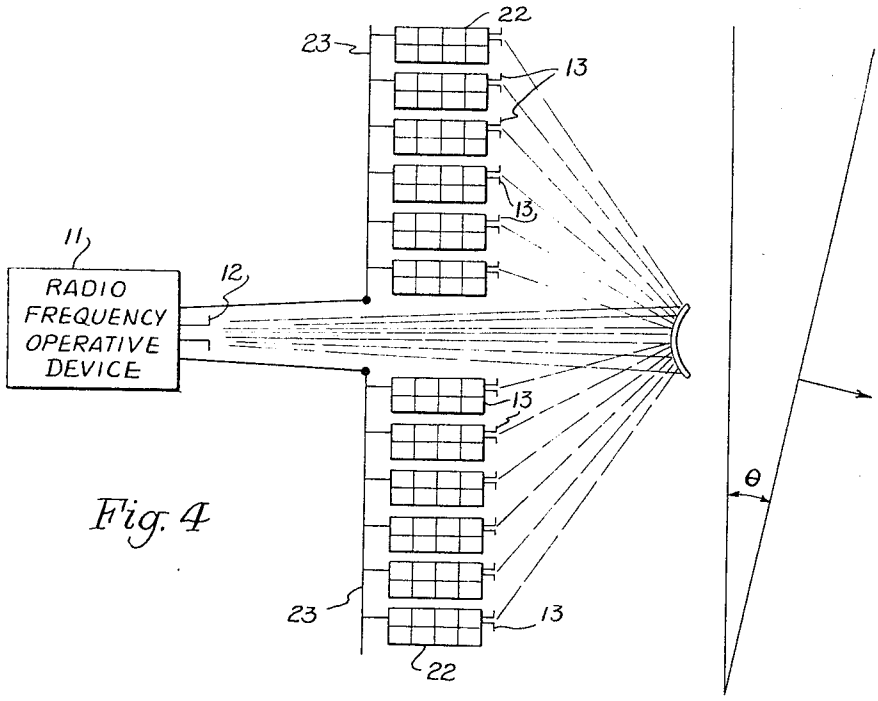


Fig. 4

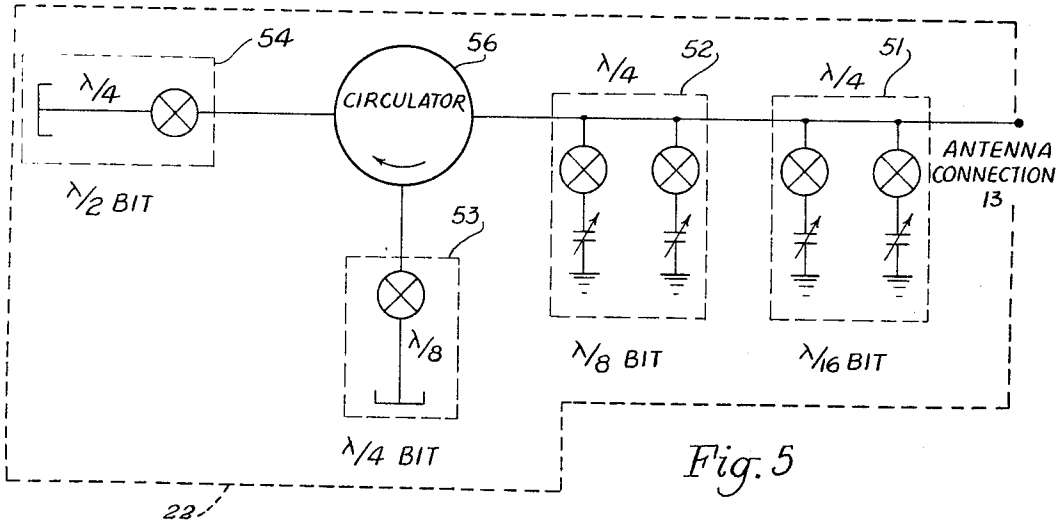


Fig. 5

INVENTOR

Kenneth S. Kelleher

BY Glenn S. Overcash

AGENT

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3,354,461

STEERABLE ANTENNA ARRAY

Kenneth S. Kelleher, 1115 Marine Drive, Alexandria, Va. 22307

Filed Nov. 15, 1963, Ser. No. 324,043
4 Claims. (Cl. 343—854)

This invention relates in general to antenna systems and in particular to directive array antenna systems wherein the phase relation of the wave energy emanating from each of the radiator elements in the array determines the beam directivity.

In many applications of radio frequency energy operative devices it is desirable to have an antenna system capable of producing a radiation pattern having a very high degree of directivity, that is, a relatively high response in a selected direction and a relatively low response in other directions. The beam produced by such an antenna system is commonly termed a "pencil beam" and is the resultant of a plurality of parallel beams of energy from respective radiator elements wherein the parallel beams have the same phase front in the selected direction. Thus, all the beam energy is additive in the selected direction whereas in other directions the beam energy is either partially or totally cancelling.

Various means for controlling the phase relation between elements in such antenna systems have been employed in the past with limited degree of success. One technique which was developed at the Naval Research Laboratory, Washington, D.C., for use in circularly polarized wave applications embodies spiral radiator elements with means for controlling the angular orientation of the elements. This technique has been disclosed and claimed in U.S. Patent 3,045,237, which issued to Arthur E. Marston on July 17, 1962. Earlier, ferrite phase shifters wherein the degree of phase shift is a function of the magnitude of an applied magnetic field were employed to establish a selected phase relation between radiator elements. Both of these prior art approaches to the phase shift control problem have presented complications which heretofore have greatly restricted the utility of phased array antenna systems. For example, the Marston technique requires the use of spiral radiator elements and thus is limited to circularly polarized wave energy applications. Moreover, the mechanical rotation of radiator elements necessitates an expensive gear train assembly which is quite cumbersome and relatively slow in operation. Likewise, the ferrite phase shifter which may be used with any type of radiator element and thus is not restricted to circularly polarized wave energy applications has severe limitations of its own. In particular, ferrite phase shifters have been found to be extremely lossy and to be highly temperature sensitive such that considerable water cooling is generally required with complex water temperature-transmitter power output compensation factors involved. It will be appreciated that the prior art devices are relatively narrow band and leave something to be desired in the frequency response area. Furthermore, all known prior art devices have been exclusively analog in nature and thus necessitate an analog-to-digital conversion for most computer programmed applications and/or are otherwise unacceptable for many uses.

Accordingly:

It is an object of this invention to provide an improved directive antenna array system which is relatively broadband.

It is another object of this invention to provide an improved antenna system of comparatively small size which can produce beamed radio frequency energy in which the

angular direction of such beamed energy can be controlled over broad angles and varied at a high rate.

It is also an object of this invention to provide an improved antenna system which is readily adaptable to beaming either circularly polarized or linearly polarized wave energy.

It is still another object of this invention to provide an improved low cost antenna system which is readily adaptable to digital programming.

It is a further object of this invention to provide an improved directive antenna array system wherein beam directivity is a function of selected changes in phase increment between radiator elements.

Other objects of the invention will become apparent upon a more comprehensive understanding of the invention for which reference is had to the following specification and drawings wherein:

FIGURE 1 is a block diagram showing of a basic phased antenna array system typical of the prior art wherein beam directivity is illustrated.

FIGURE 2 is a block diagram showing of one embodiment of the phased antenna array of the present invention.

FIGURE 3 is a more detailed showing of a phase shift means suitable for use in the embodiment of FIGURE 2.

FIGURE 4 is a block diagram showing of another embodiment of the phased antenna array of the present invention.

FIGURE 5 is a more detailed showing of a phase shift means suitable for use in the embodiment of FIGURE 4.

FIGURE 6 is a block diagram showing of a zoned embodiment of the phased antenna array of the present invention.

Briefly, the antenna array of the present invention incorporates a primary antenna which serves to illuminate a first plurality of antenna element sections, each of which includes a respective phase shifting means. Each antenna element section is adapted to receive and then to radiate the signal from the primary antenna with a presented phase relation between antenna element sections. Each of the phase shifting means is adapted to provide a phase shift in selected increments and each affords a digital control of the particular increment such that computer programming techniques may be employed in beam scanning. The antenna array is a highly compact, low cost structure and may be utilized in both linearly polarized and circularly polarized wave applications.

Referring now to the drawings:

The basic phased array of the prior art as depicted in FIGURE 1 comprises a transmitter **11**, a primary antenna **12** of the dipole variety, a first plurality of equispaced antenna elements **13** disposed in line for reception of the wave energy output of transmitter **11** via primary antenna **12**, a plurality of ferrite phase shifting means **14** which may be varied in accordance with the magnitude of the magnetic field applied by conventional means not shown; and a second plurality of antenna elements **15** disposed in line, each of which are connected via respective ferrite phase shifting means to respective antenna elements in said first plurality thereof.

In this type of array, the antenna beam position is a function of the spacing between the radiating elements and the phase difference of the energy radiated from each of the elements. Generally, in the fixed array antenna, the spacing between elements is held constant to make the beam angle a function of inter-element phase difference. When the R-F energy from each element is in phase, a phase front is formed parallel to the antenna with a main beam everywhere perpendicular to the phase front. When the phase of the R-F energy at each of the elements is

shifted so that the inter-element phase shift is constant, the phase front will angle with the plane of the antenna as shown in FIGURE 1. The main beam always forms perpendicular to the phase front such that the antenna beam angle is changed only by changes in the inter-element phase relationship. When the progressive inter-element phase shift leads rather than lags, the antenna beam is directed to the other side of broadside. Generally, this beam angle phase-shift relationship applies to both horizontal and vertical changes of beam position.

The phase front is a plane containing points of equal-phase R-F energy from adjacent radiators. The points of equal phase need not be points of energy maxima, only of equal phase. The equal-phase point of the R-F energy from adjacent radiators must also be less than one wavelength 360 degrees phase difference. A plane through the center radiator of the antenna parallel to all of the inter-radiator phase fronts represents the overall antenna phase front.

The deflection angle can be determined from the relation since $\sin\theta = a/d$, where a is the distance, in inches, from one radiator to the point where the R-F energy is in phase with the energy emitted from the next adjacent radiator. Since the inter-element spacing is in inches, it will be appreciated that the phase shift must be converted to inches to make the equation usable. The phase shift in inches, a is equal to the wavelength in inches, divided by 360, and multiplied by the angle of phase shift in degrees. For example: assuming a transmitter frequency of 3154.34 mc., a wavelength of 3.74 inches, and an inter-element phase difference of 68.6 electrical degrees, is:

$$a = \frac{3.74}{360} \times 68.6 = 0.7125$$

Since $a/d = \sin\theta$, then

$$\frac{0.7125}{1.4250} = 0.5$$

the sine of 30 degrees. From the equation it can be seen that the antenna beam is deflected 30 degrees from broadside by an inter-element phase difference of 68.6 degrees.

The embodiment of the present invention as depicted in FIGURE 2 incorporates component parts which may be substantially similar to those shown in the prior art embodiment of FIGURE 1 with at least one notable exception, in particular, the phase shifting means **21**. In this embodiment, the phase shifting means **21** does not involve an analog alteration of the wave energy in a controlled gyromagnetic medium wherein nonlinear factors of temperature, frequency, and signal power must be considered in the control thereof. Rather, in the FIGURE 2 embodiment, a true time delay is introduced in selected increments and the total time delay is a discrete sum function of these selected increments irrespective of temperature, frequency, signal power and other factors.

In this embodiment, the receive-phase-radiate (RPR) units **21** are spaced at approximately one-half wavelength centers. Each unit consists of two antennas back to back with an eight position discrete increment phase shifter in between. One of the radiating elements faces the back of the array and the other forms the front of the array. As in the prior art embodiment of FIGURE 1, the rear of the array is illuminated by standard techniques. A corporate structure is not required to illuminate each phase shift element. It has been found that air coupling between the primary antenna **12** and the illuminated antenna elements **13** results in a significant saving of space, weight and cost. Further, while there should be equal amplitude illumination of each of the elements **13**, of course, the phase front of the illumination is not especially important as the RPR units **21** can compensate for phase variation in illumination.

FIGURE 3 shows a more detailed schematic representation of one embodiment of the RPR units **21** in the antenna array of FIGURE 2. In this embodiment, three bistate switches **31**, **32** and **33** are used to select combinations of three shorted stubs **34**, **35** and **36** giving eight discrete phase shift summations ranging from zero through $\frac{7}{8}\lambda$ in $\frac{1}{8}\lambda$ increments.

As shown in FIGURE 3, the bistate switches may be three-port ferrite circulators wherein the shorted stub transmission line sections are each connected to port C of their respective ferrite circulators. In such instance, port A of circular **31** is adapted for connection to an antenna element in plurality **13** thereof, port B of circular **31** and port A of circulator **32** are interconnected by low loss transmission line **37**, port B of circulator **32** and port A of circulator **33** are interconnected by low loss transmission line **38**; and port B of circulator **33** is adapted for connection to an antenna element in plurality **15** thereof.

The circulators shown in FIGURE 3 each contain a selected configuration of gyromagnetic material so disposed that a magnetic field applied across the circulator structure will obtain a circulation of wave energy incident on any port in one selected direction clockwise or counterclockwise and a reversal of the direction of the applied magnetic field will obtain a circulation in the opposite direction. In the coaxial case, the circulators might contain two discs of ferrite equidisposed in substantially parallel relation with respective top and bottom plates of the circulators. Alternatively, in the hollow waveguide case, the circulators might contain a ferrite rod which is axially disposed in substantially perpendicular relation with respect the top and bottom plates of the circulators. In both the coaxial and the hollow waveguide circulators described above it is, of course, common practice to apply the magnetic field across the area between the top and bottom plates.

It will be appreciated that the RPR units **21** may comprise three switch sections as described above wherein discrete phase shift steps of $\lambda/8$ are provided but that it is not essential that these units comprise three switches nor that the phase shift steps be a discrete $\lambda/8$. For example, two switch sections with discrete steps of $\lambda/4$ or alternatively, four switch sections with discrete steps of $\lambda/16$ may be employed to obtain a 0 to 2π phase shift.

The phase shift increment to be selected in each application is largely determined by the permissible R.M.S. phase error and the consequent side lobe consideration. If the side lobe level is to be held to 25 db., for example, it is advisable that the phase increment $\lambda/16$ be selected assuming that a random phase error distribution over the array can be implemented. of course.

Whereas three-port ferrite circulators are of the two-state variety, these switching means are readily adaptable to 0–1, go–no-go, computer programming. That is, any phase shift 0–2π may be obtained as follows:

(1) utilizing two switches with $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ delay lines,

Switch	
I	II
Delay	
$\frac{1}{4}\lambda$	$\frac{1}{2}\lambda$
1	0
0	1
1	1
0	0

(2) utilizing three switches with ⅛λ, ¼λ and ½λ delay lines,

Switch		
I	II	III
Delay		
⅛λ	¼λ	½λ
1	0	0
0	1	0
1	1	0
0	0	1
1	0	1
0	1	1
1	1	1
0	0	0

and (3) utilizing four switches with 1/16λ, ⅛λ, ¼λ, and ½λ delay lines. In each case the delay lines are arranged such that the increment path length of each delay line is twice the path length of the preceding increment.

Switch			
I	II	III	IV
Delay			
1/16λ	⅛λ	¼λ	½λ
1	0	0	0
0	0	0	0
1	1	0	0
0	0	1	0
1	0	1	0
0	1	1	0
1	1	1	0
0	0	0	1
1	0	0	1
0	1	0	1
1	1	0	1
0	0	1	1
1	0	1	1
0	1	1	1
1	1	1	1
0	0	0	0

The systems may be programmed to achieve beam directivity as follows: (1) the elements are initially phased to produce a boresight beam compensating for phase distribution encountered at the rear of the array, if any, (2) the deviation in elevation and azimuth with respect to boresight is then calculated for the desired beam pointing direction, (3) the phase gradient required to steer the beam in elevation is then determined. This represents the exact phase shift required for the elements of each horizontal row, (4) the phase shift means in each row are set, in the eight-bit consideration, to the largest integral number of ⅛λ increments below the exact value, and (5) then the remaining fractional number of ⅛λ increment required is used to determine the portion of elements in the row which are to be increased to the next higher increment of phase shift. For instance, if the fractional

value multiplied by the number of elements in a row, for example 40, and rounded to a whole number is 18, then 18 elements in that row would be increased one step.

It will be appreciated that due to the nonreciprocal nature of the ferrite circulator used in the phase shifting means, it is necessary to change them before the system can be used in the receive mode. As mentioned in the discussion of the embodiment of FIGURE 3, the direction of circulation may be reversed by reversing the flow of current in the respective switch control means, the coils **41**, **42** and **43** which, of course, reverses the direction of the magnetic field. This operation does not require elaborate programming and can be accomplished in approximately 50 microseconds, the basic switching speed of present known ferrite circulator devices.

Although a plurality of substantially identical elemental parts are shown in the RPR unit of FIGURE 3, it is recognized that the elemental parts may be other than identical, if desired. That is, if the ferrite phase shift increment is 1/16λ, for example, and a slight degree of inaccuracy due to nonlinearity factors is permissible, other phase shift means may be substituted if warranted for one or more of the elemental parts of the phase shifting means. Other types of phase shifting means which might be incorporated in the embodiment of FIGURE 3 will be discussed hereinafter.

FIGURE 4 depicts another embodiment of the invention which may be characterized as a reflector embodiment. In this embodiment, the primary antenna **12** is disposed to illuminate a plurality of antenna elements **13** with wave energy from transmitter **11** and a plurality of phase shifting means **22** are connected with respective antenna elements to shorting means **23** such that wave energy received by the plurality of antenna elements **13** is shifted in phase, reflected, shifted in phase and then radiated by the plurality of antenna elements **13**.

FIGURE 5 shows a more detailed schematic representation of one embodiment of the RPR unit **22** in the antenna array of FIGURE 4. In this embodiment a four-bit phase shifting unit is shown and the phase increment is 1/16λ or ⅛λ, depending upon the speed of control. In the embodiment of FIGURE 5, the 1/16λ bit and the ⅛λ bit employ two diodes connected across the line and spaced ¼λ apart as the phase shift elements **51** and **52** and a three-port circulator with diode controlled shorted stubs connected to two ports thereof as the ¼λ phase shift element **53** and the ½λ phase shift element **54**. As indicated in the drawing, the ¼λ phase shift element **53** and the ½λ phase shift element **54** incorporate ⅛λ and ¼λ shorted stub sections, respectively, such that the effective overall length upon reflection is as prescribed.

It will be appreciated that for a 1/16λ phase increment, at least one phase shift element, the element **51**, must be controlled both before and after reflection in the embodiment of FIGURE 5. This does not present a capability problem in the case of spaced diodes, of course, but it is recognized that in selected applications it may be advisable to employ a fixed circulator, not shown, to permit a bypass of the phase shift element **51** upon reflection. Further, it is appreciated that other phase shift means or combinations thereof may be employed in the RPR unit **22** embodiment of FIGURE 5 as in the case of the RPR unit **21** embodiment of FIGURE 3. For example, it is within the purview of this disclosure to substitute diodes spaced ¼λ apart in conjunction with various 3 db. hybrid junctions, if desired.

Referring now to FIGURE 6, it is well recognized by those skilled in the art that, in general, phased array antenna systems have been hampered by frequency sensitivity limitations. For example, in a prior art array of 40 x 40 elements, a frequency change of 6 percent will shift the beam position by about 2 degrees when the beam is steered 45 degrees off boresight. It has been bound, however, that this limitation can be overcome by the use of a unique zoning concept.

The embodiment of FIGURE 6 is illustrative of this new and novel zoning concept which affords numerous advantages in selected applications of the present invention. In FIGURE 6, a plurality of primary radiators **12***a*, **12***b*, **12***c* and **12***d* are employed in place of the single primary radiator **12** in the prior art embodiment of FIGURE 1, and each illuminates a separate sector or zone of the antenna array. By feeding the primary radiators **12***a*, **12***b*, **12***c* and **12***d* through switchable real time delays **16***a*, **16***b*, **16***c* and **16***d*, respectively, a much closer approximation to the desired phase distribution can be achieved over a broad frequency band. It will be appreciated that this is particularly important in systems employing pulse compression or other broad-band signals.

It will be appreciated that by the use of a plurality of primary radiators with fixed time delays between zones, the bandwidth of the antenna array can be substantially increased. Thus a highly satisfactory compromise is obtained between a completely straight true time delay antenna which theoretically affords an infinite bandwidth but is exceedingly expensive, and a straight phase-phase system between elements which may be relatively inexpensive but has limited bandwidth. Furthermore, the zoning concept of this invention enables a substantial reduction in depth of the antenna array. In particular, the primary radiators may be disposed closer to the antenna elements which they illuminate and the depth can be reduced in a 20′ by 20′ array, for example, to approximately 2 to 3 feet.

The phased antenna array of this invention may constitute a planar array as shown in the several embodiments but it is not necessary that the array be planar and other configurations, for instance hemispherical or cylindrical, may be employed. This, of course, permits utilization in many applications where existing discontinuities, such as superstructure of a ship, represent a major antenna design consideration and the antenna must be adapted to minimize the effect of these discontinuities.

The RPR units **21** and **22** in the phased arrays of the present invention are especially well suited to modular antenna array assemblies of the variety disclosed herein. It has been found that the antenna face can be easily fabricated such that either a single RPR unit or a row of RPR units may be removed for maintenance. Furthermore, in an operational system it is recognized that a simple scanning probe sampling of the near field can be used to sense the operation of the phase shift units and give a GO or NO-GO decision on each unit. This monitoring of the RPR units can be done concurrently with radar operation in many cases.

It will be appreciated that the primary radiator **12** of the antenna array system may be other than a single dipole feed horn, as shown, and that multiport horn assemblies of various varieties may be substituted in accordance with standard practice in the art for monopulse operation if desired. Likewise if a multiport primary radiator or if more than one primary radiator is employed, sequential lobing techniques may be employed in a selected primary radiator energization pattern if desired.

Moreover, the primary radiator may be the output reflector element of a cassegrain feed system wherein the actual primary radiator is directed at the reflector element from a remote point which may be on the opposite side of the antenna array or elsewhere.

It is understood, of course, that the antenna array of this invention is not restricted to the use of any particular type of antenna element and that in the lens embodiment of FIGURES 2 and 6, for example, the antenna elements in the two pluralities thereof may be different if desired. Also, it is within the purview of this disclosure to use different types of antenna elements within the several pluralities of elements or to alter selected elements within these pluralities for directional or other purposes.

Finally, it is understood that this invention is to be limited only by the scope of the claims appended hereto.

What is claimed is:

1. A steerable antenna array comprising

transmitter means,

first antenna means coupled to said transmitter means for radiating electromagnetic wave energy,

first reflector means for reflecting the wave energy from said first antenna means,

second antenna means for receiving the reflected wave energy,

phase shifting means coupled to said second antenna means, said phase shifting means including

a three-port ferrite circulator and

a plurality of phase shift elements having diode-controlled transmission line sections of a predetermined electrical length to give a desired delay when switched in the transmission path, and

second reflector means for reflecting the wave energy from said phase shifting means back through said phase shifting means for radiation by said second antenna means.

2. A steerable antenna array comprising

transmitter means,

first antenna means coupled to said transmitter means for radiating electromagnetic wave energy,

said first antenna means comprising a plurality of individual transmitting antennas having

delay means coupled between each individual transmitting antenna and said transmitter means,

second antenna means for receiving said radiated electromagnetic wave energy, said second antenna means including a plurality of individual receiving antennas,

said second antenna means comprising zones which include groups of individual receiving antennas associated with predetermined individual transmitting antennas to produce a desired phase distribution over a broad frequency band;

phase shifting means coupled to each of said receiving antennas of said second antenna means, said phase shifting means comprising

a plurality of serially-connected switch means, each of said switch means having connected thereto a shorted transmission line section of a predetermined electrical length selected to give a desired delay when switched in the transmission path either alone or in combination with other line sections, and

third antenna means comprising an individual transmitting antenna coupled to each of said phase shifting means for transmitting electromagnetic wave energy to produce a combined phase front having a predetermined desired angle of deflection.

3. The combination according to claim **2** wherein

said switch means comprise three-port ferrite circulators.

4. The combination according to claim **2** wherein

said phase shifting means provide discrete sequential phase increments, each increment being twice the preceding increment.

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HERMAN KARL SAALBACH, *Primary Examiner.*

ELI LIEBERMAN, *Examiner.*

C. BARAFF, *Assistant Examiner.*