June 26, 1962 F. E. GOODWIN ET AL 3,041,605

ELECTRONICALLY SCANNED ANTENNA SYSTEM

Filed Nov. 28, 1958 4 Sheets-Sheet 1

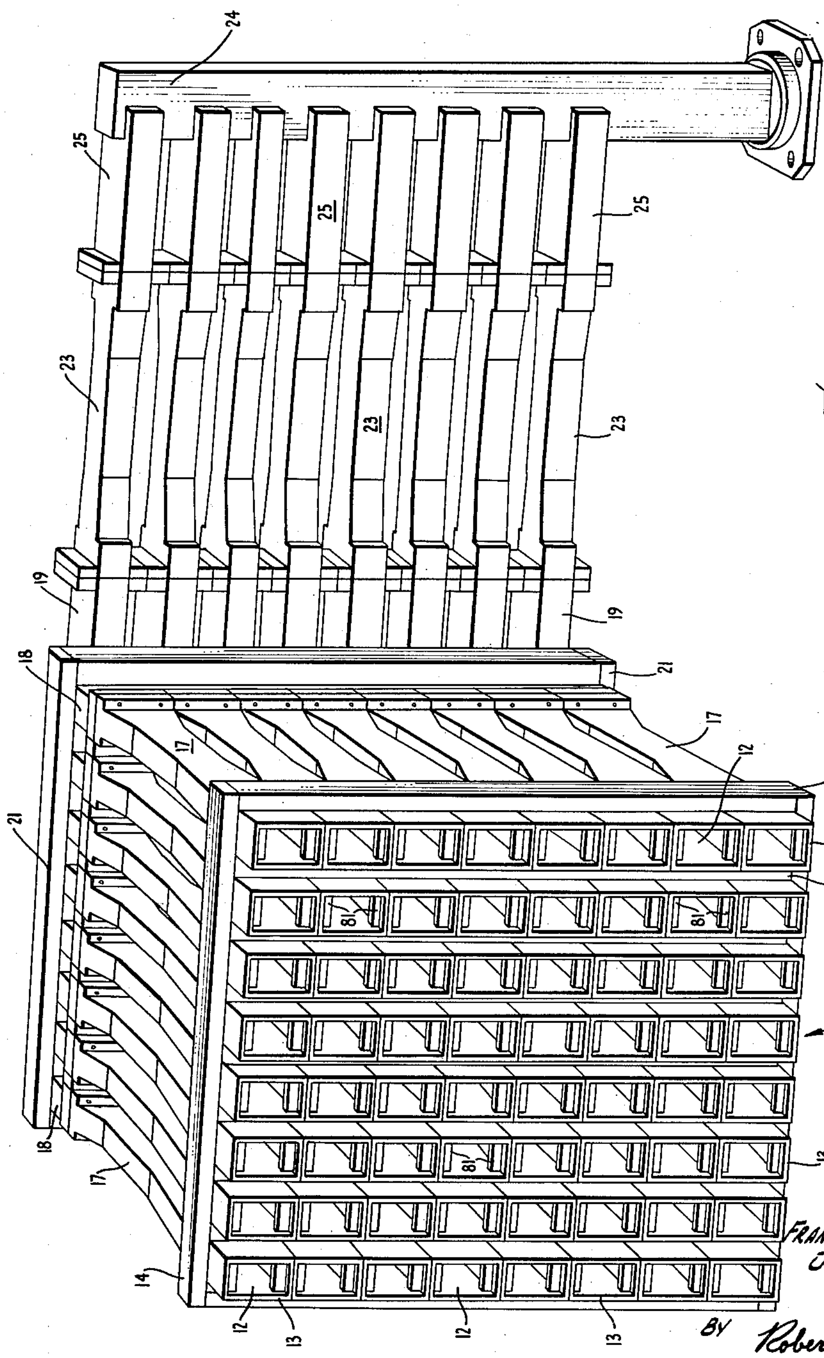


FIG. 1.

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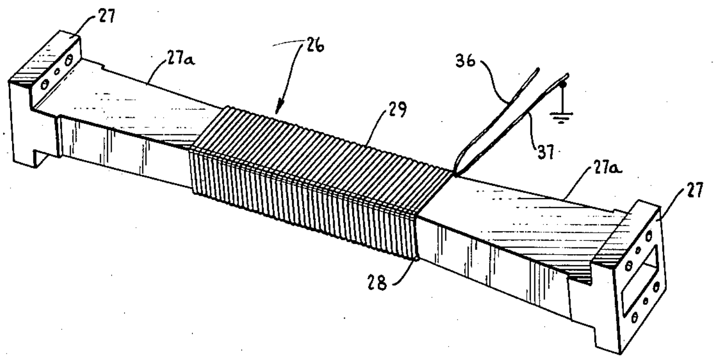
FIG. 2.



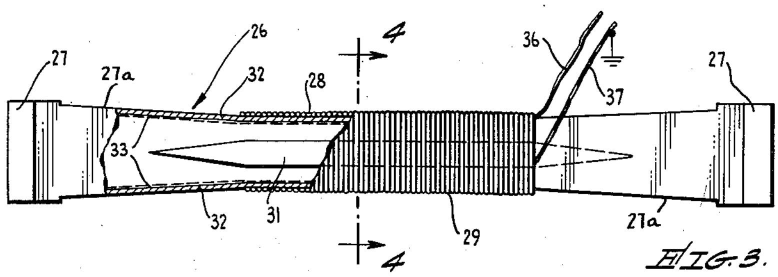




FIG. 3.

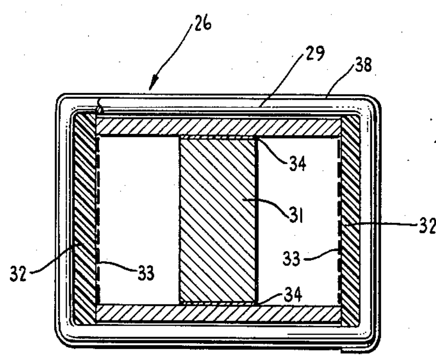



FIG. 4.

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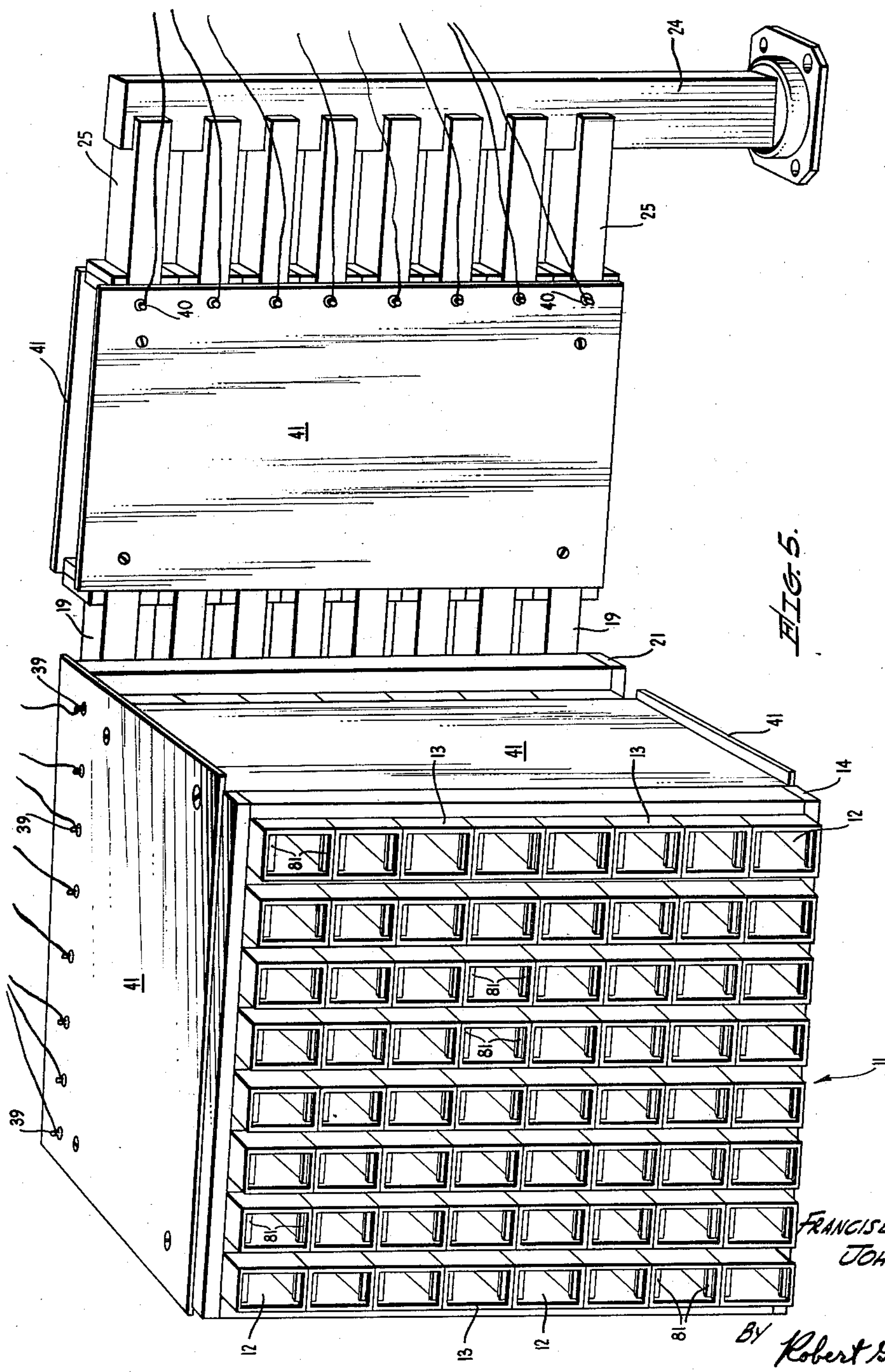


FIG. 5.

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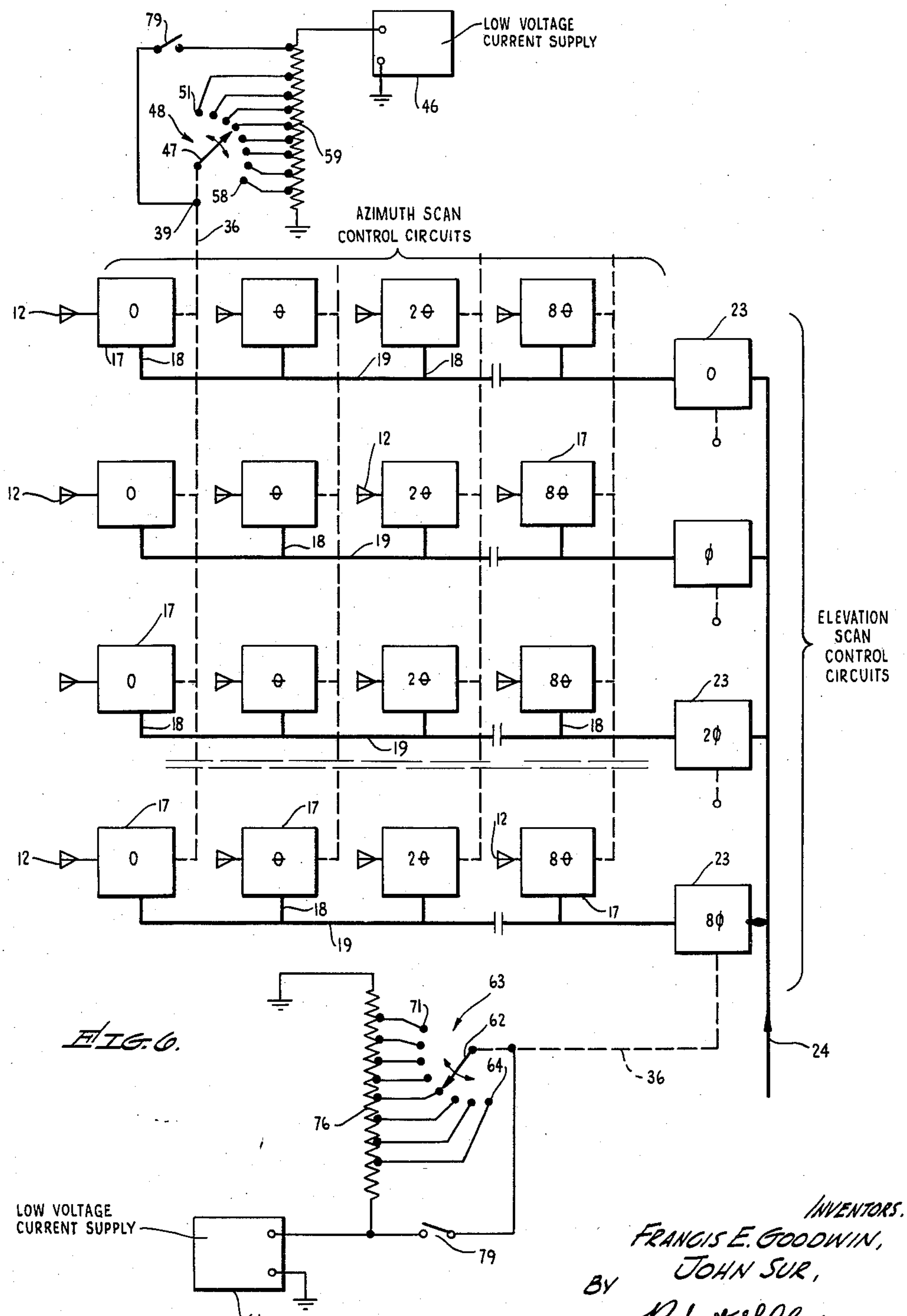


FIG. 6.

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United States Patent Office

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Patented June 26, 1962

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# 3,041,605
# ELECTRONICALLY SCANNED ANTENNA SYSTEM

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Filed Nov. 28, 1958, Ser. No. 777,550
7 Claims. (Cl. 343—100)

The present invention relates to an electronically scanned antenna system and more particularly to an antenna system having a plurality of reciprocal phase shifters programmed to provide a raster type volumetric scan from a fixed type antenna.

The disadvantages of mechanical types of scanning are well known in the art and to overcome such disadvantages a number of antenna system have been developed employing a variation of the frequency of microwave energy utilized to excite the antenna. Most of such systems provide electrical scanning of space in one dimension, but still require mechanical movement of the antena to include a second dimension.

With the recent advancement in the development of microwave components having elements of a ferromagnetic dielectric material, it becomes possible to have an electronically scanned antenna system for two-dimensional scanning of space; however, such phase shifters as developed to date have not met the exacting characteristics or requirements necessary for such a system. The referenced characteristics include phase shift reciprocity, accurate high speed switching, economy of driving power, small physical size, temperature compensation, and high power handling capabilities.

It is, therefore, an object to provide a new and improved electronic beam forming and steering antenna system.

Another object is to provide a fixed frequency antenna system for volumetric scanning having a minimum number of control circuits for the phase shifters.

A further object is to provide an antenna system requiring a minimum number of control circuits equal to two times the number of radiating elements in one dimension of the antenna array.

A further object is to provide a new and improved phase shifter having characteristics that meet the requirements for inclusion in an electronic beam forming and scanning antenna system.

A still further object is to provide a phase shifter having a ferromagnetic dieletcric material extended between reduced broad walls of a rectangular waveguide with a static magnetic field through the material parallel to the axis of the waveguide.

In brief, the electronically scanned antenna system of the present invention comprises a plurality of radiating elements mounted in a two-dimensional array. Microwave excitation energy is fed to the array by a rectangular waveguide coupled to individual feeder waveguides for each horizontal row with a separate reciprocal phase shifter included in each of such couplings. Also, separate similar phase shifters are provided between the feeder waveguides and the radiating elements. The azimuthal angle of the beam from such antenna array is controlled by the relative phase of the microwave energy between the vertical rows. In a similar manner the elevational angle of the beam is controlled by the relative phase of the microwave energy between the horizontal rows. Thus, for an antenna array of $n$ by $m$ elements, where $n$ and $m$ are equal and arranged with the same number of vertical and horizontal rows, a raster type scan is obtained with a minimum number of $n+m$ control circuits for the phase shifting elements.

As stated previously, the reciprocal phase shifters are the same and comprise, in general, a section of rectangular waveguide with a portion of the broad wall dimension reduced. A solenoid is wound about the waveguide at the reduced dimension to produce a longitudinal magnetic field through an element of ferrite material mounted centrally within the waveguide between the broad walls. When the magnetic field is established at different values, the permeability of the ferromagnetic material is changed and results in altered values of the propagation constant of the waveguide and thereby the phase of microwave energy as it is propagated therethrough.

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Other objects and advantages will be apparent from the following description and claims considered together with the accompanying drawing in which:

FIG. 1 is a perspective view of the waveguide structure of a partially assembled two-dimensional antenna array of the present invention;

FIG. 2 is a perspective view of a phase shifter as employed in the array of FIG. 1;

FIG. 3 is a schematic and perspective view, partly in section, of the phase shifter of FIG. 2;

FIG. 4 is an enlarged cross-sectional view of the phase shifter of FIG. 2, as taken along the line 4—4 of FIG. 3;

FIG. 5 is a perspective view of an assembled antenna array of the present invention; and

FIG. 6 is a schematic view of the antenna array of FIG. 5 together with the necessary schematically shown control circuits.

Referring to FIG. 1 of the drawing, there is illustrated the rectangular waveguide structure of a two-dimensional antenna array **11** having a plurality of radiating elements **12**, which in the present example comprise open ended sections of rectangular waveguides **13**. As shown, the array **11** has 64 radiating elements **12**, which are suitably mounted in an 8 by 8 matrix within a first supporting frame **14**.

For a substantially small total angle of scan, about 40 degrees by 60 degrees without second order beams, the space between radiating elements **12** of the matrix is established at one inch in both the horizontal and vertical directions. Vertically disposed spacers **16** mounted between elements of the frame **14** provide a radio frequency choke and also the necessary horizontal spacing between the radiating elements **12** while the vertical spacing is provided by the waveguides themselves, as stacked. The foregoing specifications are for an X-band antenna where the operating frequency is 8820 mc. so that the spacing is considerably more than one half of the free space wavelength of the energy. It will be readily apparent that by decreasing the spacing between the radiating elements **12** to one half of the free space wavelength the useful solid scan angle is increased to the order of 90 degrees by 90 degrees. With respect to the foregoing selection of a matrix of 64 radiating elements, it is to be noted that such number is merely an example and provides a beam having a 12 degree spread, whereas by increasing the number of radiating elements the beam spread is decreased to a more desirable pencil shape for radar applications.

The open ended rectangular waveguides **13** thus provide the radiating elements **12** and are coupled to a similar plurality of rectangular waveguides **17**, each having a reciprocal phase shifting element as will be set forth more fully hereinafter. The extended ends of the waveguides **17** are coupled by short coupling rectangular waveguides **18** to parallel and horizontally disposed rectangular feeder waveguides **19**, one for each horizontal row of the matrix. Such feeder waveguides **19** are disposed perpendicular to the waveguides **13** with the broad walls also respectively perpendicular and electromagnetic coupling therebetween is accomplished through conventional slanted narrow wall slots (not shown) in the waveguides **19**.

A second supporting frame **21**, similar to the first frame

14, is mounted about the coupling waveguides **18** to aid in maintaining the fixed relationship between the radiating elements **12** and both frames may be suitably secured to a stationary platform. The feeder waveguides **19** are extended by separate rectangular waveguide sections **23**, each having a phase shifting element similar to those to be described with respect to waveguides **17**. To supply microwave energy to the waveguide system just described, a single rectangular waveguide **24** is provided for suitable coupling to a source of microwave energy (not shown) and extended perpendicular to the waveguide sections **23** with the broad walls respectively perpendicular and with electromagnetic coupling again accomplished by conventional narrow wall slots (not shown) and substantially in the single waveguide **24** and short-length rectangular waveguide sections **25**.

Referring now to the waveguides **17** and **23**, in detail, there is shown in FIG. 2 a perspective view of a typical waveguide (indicated generally by numeral **26** for reference purposes) having a reciprocal phase shifting element. Coupling flanges **27** are provided at either end along the transverse dimension of the broad walls of rectangular waveguide **26** for suitable connection to other waveguides, in accordance with the foregoing. By omitting similar coupling flanges along the narrow walls of the waveguides **26**, a plurality of such waveguides may be suitably bound together with portions of the narrow walls of adjacent waveguides touching and the desired distance between radiating elements **12** obtained.

Adjacent to each end of the waveguide **26** there is provided a tapered portion **27*a*** to reduce the broad wall dimension by a predetermined amount such, for example, as from .9″ to substantially .6″ for conventional RG–52 waveguide. A straight center portion **28** at the reduced broad wall dimension then extends between the tapered portions **27*a***. It is to be noted that the tapered portions **27*a*** provide minimum impedance mismatch for microwave energy propagated therethrough in that there are no abrupt discontinuities in the walls of the waveguide. Thus, when waveguides **26** are stacked with narrow walls of adjacent waveguides facing each other, there is a space between the two walls for accommodating the turns of solenoids **29** as wound about the center portions **28**.

As stated previously each of the waveguides **26** is provided with a phase shifting element, which, as illustrated in FIG. 3, comprises an elongated substantially thin slab **31** of a ferromagnetic dielectric material, such as ferrite, having a permeability that is variable with variation of an applied magnetic field. The ferrite slab **31** is mounted centrally within the center portion **28** of the waveguide **26** parallel to the narrow walls and transverse to the reduced broad walls, as best shown in FIG. 4. To minimize voltage reflections from the ferrite slab **31** both ends thereof are tapered to a point or wedge which extend from the center portion **28** into the respective tapered portions **27*a***. It is to be noted that the reduced broad wall dimension of .6″ is beyond the cutoff of the waveguide **26** at X-band frequencies; however, it has been found that energy propagation is normal when the ferrite slab **31** is mounted in the waveguide in the above specified manner.

In accordance with the invention, it is necessary that changes in phase shift be accomplished with high speed at small average values of magnetic field establishing current. One step toward realization of such characteristics is embodied in the reduction of the broad wall dimension of the waveguide **26** at the center portion **28**. Though this referenced reduction was necessary to achieve sufficient space between stacked waveguides **26** for the placement of the windings of solenoids **29**, it also provides a minimized length of path for a magnetic field established by the solenoid longitudinally through the ferrite slab **31**. This means that a given value of magnetization of the ferrite slab **31** is accomplished by a lesser number of solenoid ampere-turns than is possible with a longer path; that is, the smaller the diameter of the solenoid, the more concentrated the axial portion of the magnetic field for a given value of excitation current.

A second step toward obtaining fast switching of phase with such structure is accomplished by minimizing the shorted-turn effect of the walls of the waveguide **26**. This accomplishment is embodied in the utilization of substantially thin conductive walls, which may be a ceramic type of waveguide with the inside surfaces having a thin coating of conductive material. Preferably, however, for reasons to be set forth hereinafter, the waveguide **26** is shaped from a rectangular section of RG–52 waveguide by milling off the sides or narrow walls and then reducing the dimensions of the broad walls to those previously specified. The resulting open sides are then covered with an insulating material **32**, such as plastic, having a thin conductive layer **33**, such as one mil brass or copper foil. The foil **33** is then conductively connected to the remaining walls of the waveguide **26**, as by sweat soldering. Thus, when current flows through the solenoid **29** there is a minimum of eddy current losses and the one mil foil is sufficient to prevent radio frequency leakage losses.

Having reduced the physical size of the phase shifter waveguide **26** over previously known devices of this type and provided fast switching with low values of magnetic field establishing current, another required characteristic relates to temperature compensation. With respect to this characteristic, it is to be noted that when a ferrite material is magnetized in the presence of microwave energy, heat is developed in the ferrite and this results in a change of permeability. Since the propagation constant is a function of permeability, changes in temperature alter the propagation constant and thereby change the degree of phase shift of propagated energy with other variables held constant. To minimize temperature effects the ferrite slab **31** is mounted in the waveguide **26** in thermal contact with the broad walls which are of conventional thickness and thereby provide a suitable heat sink. To improve the phase shift efficiency a thin layer **34** of thermal conducting ceramic, such as boron nitride or barium oxide, is disposed between the ferrite slab **31** and the broadwalls of the waveguide **26** and thermal conductivity is thereby maintained.

With the phase shifter waveguide **26** assembled in the foregoing manner with leads **36** and **37** of the solenoid suitably connected to a source of current, a flow of current through the solenoid establishes a magnetic field axially within the waveguide and through the ferrite slab **31**. This magnetic field establishes the permeability of the ferrite material of the slab **31** at a certain value and therefore sets the propagation constant of the waveguide so that microwave energy as propagated through has a difference in phase between the respective ends. Because the slab **31** is centered in the waveguide **26** along the plane of maximum electric field, energy in the dominant mode which is propagated in either direction is similarly shifted in phase. With the solenoid **29** having about 160 turns the phase shifter waveguide **26**, as previously described, provides a zero to 360 degree phase shifting time on the order of one microsecond, which is a great improvement over the minimum .5 second switching time obtainable with prior art devices. Also minimum temperature effects with respect to the ferrite slab are achieved by the thermally conductive contact between the slab and the broad walls of the waveguide **26**.

Having described the phase shifting waveguides **17** and **23** in detail the final assembly of the antenna will now be set forth with reference to the perspective view of FIG. 5. Each of the waveguides **17** and **23** of FIG. 1 is provided with a solenoid **29** and to prevent interaction of the magnetic fields of adjacent solenoids, magnetic shielding is provided such as a thin layer **38** (see FIG. 4) of magnetic iron sheeting suitably secured about the windings of each of the solenoids. To prevent free circulation of air about the assembled phase shifting waveguides 17 and 23 and to provide mounting of electrical terminals 39 and 40 for connection of azimuth and elevation scan control circuits, respectively, panels 41 of an electrical insulation material, such as phenolic, are suitably mounted to respectively cover the open sides of such waveguide assemblies.

For some installations where the surrounding temperature is substantially constant as in some land-based installations, the heat sink effect provided by the brass walls of the waveguides is sufficient to maintain a substantially constant temperature for the ferrite elements after a relatively short warm-up period of operation. In other installations it may be necessary to provide heater elements within the enclosure formed by the panels 41 with conventional thermostatic control elements coupled to the heaters. In both such instances temperature-change effects are minimized with respect to the phase shifting ferrite elements 31 so that a given value of magnetization of the ferrites provides in each instance substantially the same degree of phase shift of the propagated microwave energy. Additionally, in some installations, it may be necessary to provide a dielectric material to cover the open ends of the radiating elements 12 to prevent a flow of external air from reaching the ferrite elements 31 through such openings.

To control the azimuth scan of the beam from the assembled array 11 one lead 36 of each of the solenoids 29 of one vertical row of phase shifters is connected to one of the terminals 39. The referenced terminal 39 is connected to a movable contact 47 of a conventional stepping switch 48 having in the present example 8 fixed contacts 51–58. A precision resistor 59 is connected between the output terminals of the source 46 and separate taps of such resistor are respectively connected to the fixed contacts 51–58 to provide a different value of voltage for each contact. A similar stepping switch 48 and current control circuit is provided for each of the remaining vertical rows of solenoids 29 and because of the similarity only one such switch and circuit has been illustrated in FIG. 6 and described in detail. One difference with respect to the stepping switches 48 is to be noted and this relates to the relative positions between the movable and fixed contacts respectively, which is established so that successive switches apply incrementally increased values of current.

With respect to the elevation scan control circuits one lead 36 of one solenoid 29 of the vertical phase shifters is connected to a movable contact 62 of another conventional stepping switch 63 having 8 fixed contacts 64 to 71. Again a precision resistor 76 is connected between the output terminals of the current source 61 with taps respectively connected to the fixed contacts 64 to 71 to provide incremental values of current to the solenoid 29. Additional stepping switches 63 and associated control circuit connections are the same for the remaining solenoids of the phase shifter 23 and only one is detailed in FIG. 6 for clarity of illustration. As with the phase shifters 17, phase shifters 23 are provided with successively increased increments of current for any one position of the stepping switches 63.

Thus, by separately and simultaneously operating the stepping switches 48 and 63, a beam radiated by the 64 elements of the antenna array 11 may be readily controlled in azimuth and elevation by the establishment of phase differences between the microwave energy fed to respective vertical rows of radiating elements and of phase differences between the horizontal rows of radiating elements. With the improved methods of manufacturing ferrite materials the selection and forming-to-size of those elements operated in parallel relation to provide substantially equal phase shifts for a given value of magnetic field is relatively simple. It is also to be noted that should hysteresis effects occur in the ferrite elements of the phase shifter 17 and 23 during the switching period, such effects may be readily minimized by applying a current to solenoids 29 resulting in a saturating field through the elements during this period, as conventionally indicated by switches 79, which may be mechanically linked to the associated stepping switch 48, 63.

While the scanning control circuits have been set forth in detail with respect to the combination of precision resistors 59, 76, and stepping switches 48, 63, it is to be noted that suitably timed conventional electronic circuitry, either vacuum tube or transistor, may be readily provided with the timing programmed by a simple computer. This latter consideration is to be particularly considered where a faster rate of scan is desired than the approximate 30 scans per minute, which is permissible with the stepping switches 48 and 63, as described, and which are limited to a switching time of about 32 per second.

In the presently described embodiment of the invention the radiating elements 12 are inductive matched irises formed by the open ends of waveguides 13 with inductive side plates 81 mounted between the broad walls to extend interiorly and perpendicularly from the narrow walls. While the inductive matched iris type of radiating element 12 is suitable for a total scan angle of about 40 degrees, other types may be desirable for larger scan angles and these are within the knowledge of the art.

Consider now the operation of the antenna system, as described in detail in the foregoing, with reference being made to the drawing and particularly to FIG. 6. Microwave energy is introduced to the input of waveguide 24 and propagated therethrough in the dominant mode. A portion of the energy is electromagnetically coupled from waveguide 24 into each of the phase shifters 23 in the conventional manner. The stepping switches 63 associated with the respective solenoids 29 of the phase shifters 23 respectively establish incrementally different values of current through the solenoids and this results in incrementally different values of magnetic field through the phase shifting ferrite slabs 31. Thus, with suitable settings of the initial and subsequent positions between the movable and fixed contacts of the stepping switches 63, the permeability of the slabs 31 is established to provide relative phase shifts between zero and 360 degrees in successive 45 degree steps for the example shown. Thus, the microwave energy propagated by the eight feeder waveguides 19 differs in phase by 45 degrees between adjacent waveguides and, since each of the waveguides feeds a single horizontal row of eight radiating elements 12, the relative phase of the energy of the adjacent rows determines the elevational angle of the resulting beam.

The phase shifters 17 coupled between feeder waveguides 19 and the individual radiating elements 12 are similarly controlled; however, the phase shifters of each vertical row are controlled to provide a similar shift in the phase of the microwave energy for each such row. Thus, by suitable settings of the initial and subsequent positions between the moveable and fixed contacts of the stepping switches 48, the relative phase of the microwave energy of vertical rows of radiating elements 12 is established. The azimuthal direction of the beam may then be readily established by proper control of the operation of the stepping switches 48.

In the foregoing it has been shown that the direction of the beam is controlled in azimuth by the stepping switches 48 and in elevation by the stepping switches 63. When the two sets of stepping switches 48 and 63 are simultaneously operated from a position where the relative phase of one radiating element 12 is zero, a raster type beam scan of space is readily obtained. This latter operative relationship is shown in FIG. 6 where the phase shifters 23 are indicated as introducing phase shifts varying by incremental angles from zero to 8 $\phi$ from top to bottom and the phase shifters **17** are indicated as introducing by vertical rows similar phase shifts varying by incremental angles from zero to 8 $\theta$ from left to right. With the phase shifters **23** of the feeder waveguides maintained in the same condition, operation of the stepping switches **48** to shift the relative phases of the vertical rows to the right results in azimuth translation of the beam. When the relative phases of the radiating elements **12** are in reversed order from the initial relationship set forth above, the stepping switches **63** are operated to alter the phase condition of the feeder waveguides **19** so that the zero—zero phase shift relation between the two sets of phase shifters **17** and **23** coincides at the left column, second row down. By continuing the foregoing operation procedure, an 8 by 8 raster is scanned and, since the phase shifters **17** and **23** are reciprocal, return echos are received for application to a receiver as is usual in conventional radar equipment.

There has been set forth in the foregoing a reciprocal phase shifter having accurate high speed switching, economy of driving power, and small physical size for an all-phase shifter type of volumetric scanning antenna system requiring a minimum number of control circuits. This antenna system is capable of raster-type scan of space covering 90 degrees by 90 degrees with a pencil type beam.

While the salient features of the invention have been described in detail with respect to one embodiment, it will be readily apparent that numerous modifications may be made within the spirit and scope of the invention and it is, therefore, not desired to limit the invention to the exact details shown except insofar as they may be set forth in the following claims.

What is claimed is:

1. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* columns along the other dimension, waveguide means for coupling said radiating elements to a source of fixed-frequency microwave energy, said waveguide means including a first phase shifting means for varying the phase of said energy between adjacent *n* rows, said waveguide means including second phase shifting means for varying the phase of said energy between adjacent *m* rows.

2. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* rows along the other dimension, a similar plurality of variable phase shifters respectively coupled to said radiating elements and having separate control elements, a source of high frequency energy, separate variable phase shifting means coupled between phase shifters of each *m* row of radiating elements and said source with each such means having separate control elements, first control means coupled to the control elements of said phase shifters disposed along *n* rows for establishing a predetermined phase shift of energy for each *n* row and phase difference between adjacent *n* rows, and second control means coupled to the control elements of said phase shifting means for establishing a predetermined phase shift of energy for each *m* row and phase difference between adjacent *m* rows, whereby subsequent separate adjustments of said first and second control means provides beam scanning by *m* plus *n* control means.

3. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* rows along the other dimension, a first plurality of variable phase shifters respectively coupled to said radiating elements, a source of fixed-frequency microwave energy, a second plurality of variable phase shifters respectively coupled between phase shifters in *m* rows of said first plurality and said source, each of said first and second plurality of phase shifters having elements of a ferromagnetic dielectric material with variable permeability, first control means coupled to said first plurality of phase shifters for varying the permeability of the elements by rows with the variation in each row being to the same degree to establish different values of permeability between adjacent *n* rows, and second control means coupled to the second plurality of phase shifters for individually varying the permeability of the elements thereof to establish different values of permeability between adjacent *m* rows, whereby subsequent separate adjustments of said first and second control means provides beam scanning by *m* plus *n* control means.

4. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of rectangular waveguides mounted in parallel relation to provide at ends thereof a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* rows along the other dimension, rectangular waveguide means coupled between said plurality of waveguides by *m* rows to a source of fixed-frequency microwave energy, said waveguide means including means for varying the phase of said energy between adjacent *n* rows and separate means for varying the phase of said energy between adjacent *m* rows, and a programmer coupled to said means for varying the relative phases to provide a raster-type beam scanning pattern.

5. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* rows along the other dimension, waveguide means for coupling said radiating elements by *m* rows to a source of fixed-frequency microwave energy, said waveguide means including first ferrite phase shifters with one for each radiating element and separate second ferrite phase shifters between said first phase shifters and said source with one for each *m* row, separate solenoids wound on said waveguide means for each of said first and second phase shifters, means for selectively connecting said solenoids of said first phase shifters by *n* rows to different current sources, means for selectively coupling solenoids of said second phase shifters to different current sources, and means for programming relative values of current of said current sources to provide a raster type scan with a radiated beam of said microwave energy.

6. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of rectangular waveguides mounted in parallel relation to provide at ends thereof a plurality of radiating elements geometrically spaced in a two-dimensional array with *n* rows along one dimension and *m* rows along the other dimension; a first plurality of phase shifters; a source of fixed-frequency microwave energy; a second plurality of phase shifters coupled between phase shifters of said first plurality by *m* rows and said source of microwave energy; each of said first and second plurality of phase shifters comprising a section of rectangular waveguide having a portion with reduced broad wall width accommodating a solenoid wound thereabout and with a ferrite slab mounted centrally within such portion perpendicular to and in thermal contact with the reduced broad walls, and a magnetic shield disposed about said solenoid; means for selectively connecting said solenoids of said first plurality of phase shifters by *n* rows to different current sources; means for selectively coupling solenoids of said second plurality of phase shifters to different current sources; and means for programming relative values of current of said current sources to provide a raster type scan with a radiated beam of said microwave energy.

7. In a system for volumetric scanning with a radiated beam, the combination comprising a plurality of rectangular waveguides mounted in parallel relation to provide at ends thereof a plurality of radiating elements geo-

metrically spaced in a two-dimensional array with $n$ rows along one dimension and $m$ rows along the other dimension; a first plurality of phase shifters; a source of fixed-frequency microwave energy; a second plurality of phase shifters coupled between phase shifters of said first plurality by $m$ rows and said source of microwave energy; each of said first and second plurality of phase shifters being reciprocal and comprising a section of rectangular waveguide having a portion with reduced broad wall width, tapered transition portions extended at either end of said reduced portion, nonconductive narrow walls with thin conductive layers on interior surfaces, a ferrite slab mounted centrally within such portion perpendicular to and in thermal contact with the reduced broad walls, a solenoid wound about the reduced portion and accommodated thereby, and a magnetic shield disposed about said solenoid; means for selectively connecting said solenoids of said first plurality of phase shifters by $n$ rows to different current sources; means for selectively coupling solenoids of said second plurality of phase shifters to different current sources; and means for programming relative values of current of said current sources to provide a raster type scan with a radiated beam of said microwave energy.

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