United States Patent [19]

Harrison et al.

[11] 3,858,221

[45] Dec. 31, 1974

[54] **LIMITED SCAN ANTENNA ARRAY**

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[22] Filed: **Apr. 12, 1973**

[21] Appl. No.: **350,412**

[52] **U.S. Cl.** **343/815,** 343/844, 343/846, 343/854

[51] **Int. Cl.**...... **H01q 1/48,** H01q 3/26, H01q 21/12

[58] **Field of Search** 343/854, 872, 813, 815, 343/824, 844–846, 853

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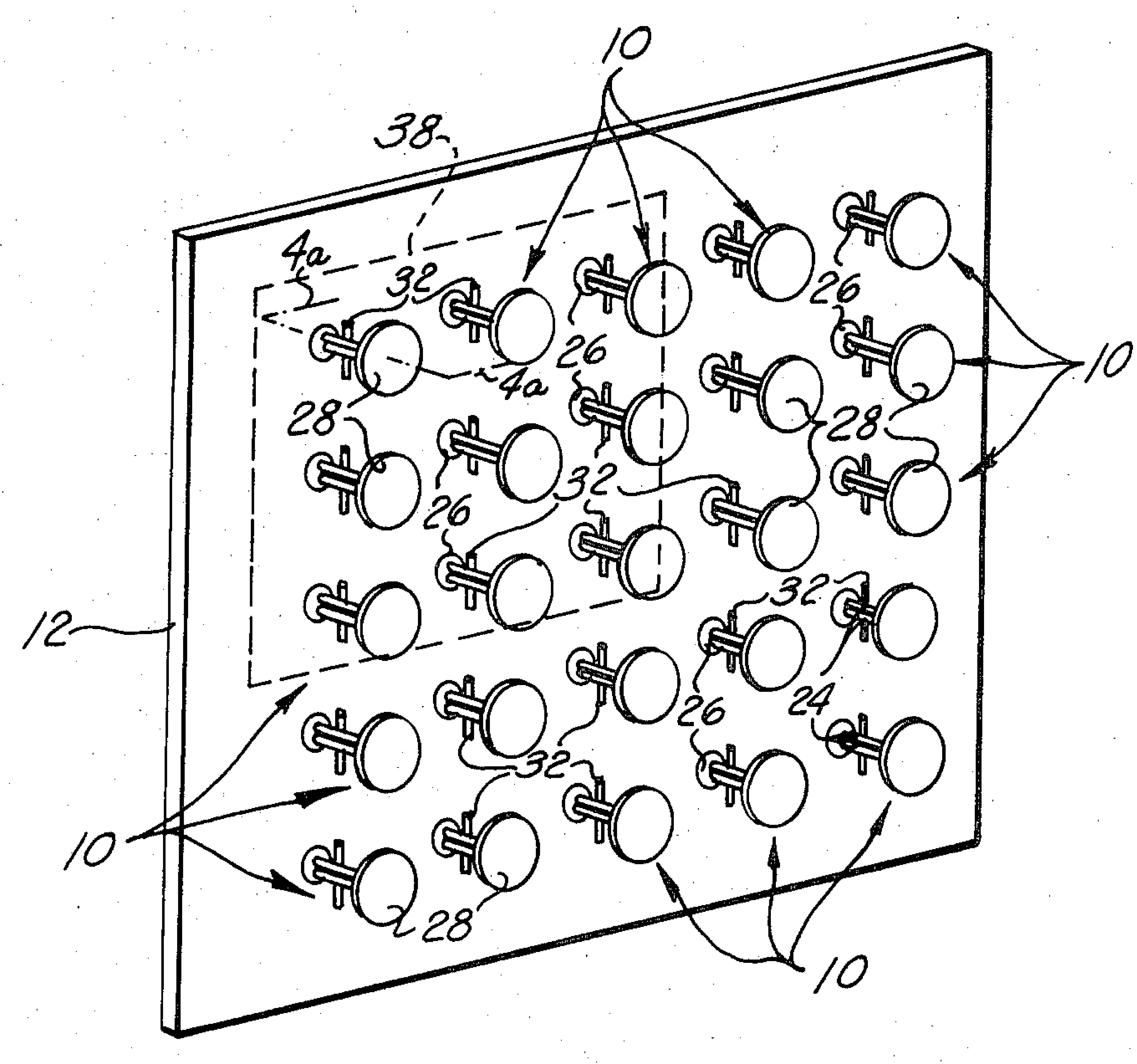
Primary Examiner—James W. Lawrence
Assistant Examiner—Marvin Nussbaum

[57] **ABSTRACT**

An electronically steerable antenna array comprising phased element antennas has essentially uniform gain for small scan angles. An idealized shape of element pattern in the array environment is closely approached by controlling the complex mutual coupling among the element antennas for pattern shaping. The resulting element-in-array pattern has a nearly flat top, steep sides, and also has low sidelobes in the angular regions where grating lobes of the array factor can appear upon steering. Consequently, the antenna array has high and almost constant gain over a limited range of steering angles in all directions from the principal mechanical axis of the planar array, and has low sidelobes and low grating lobes.

12 Claims, 12 Drawing Figures



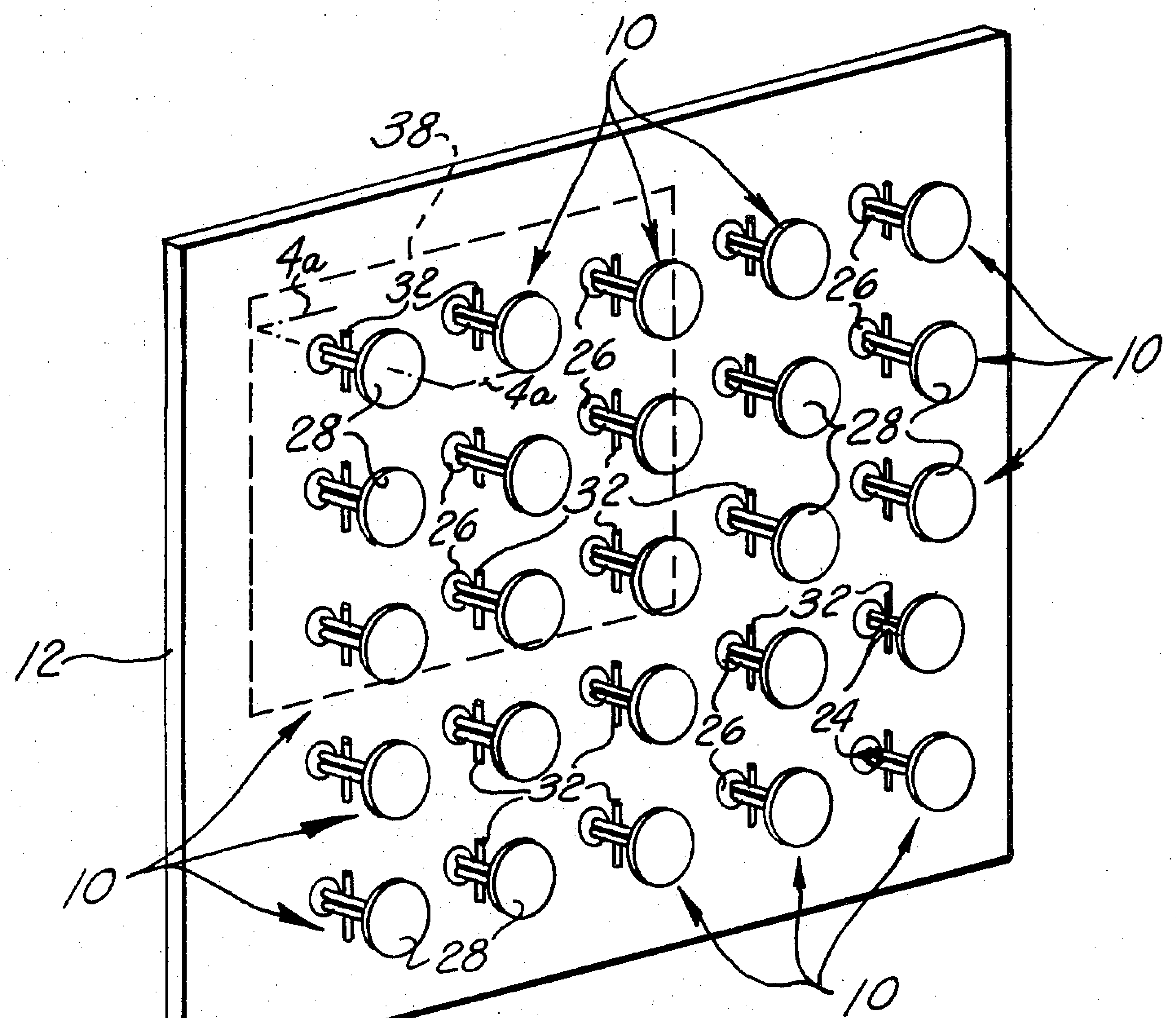
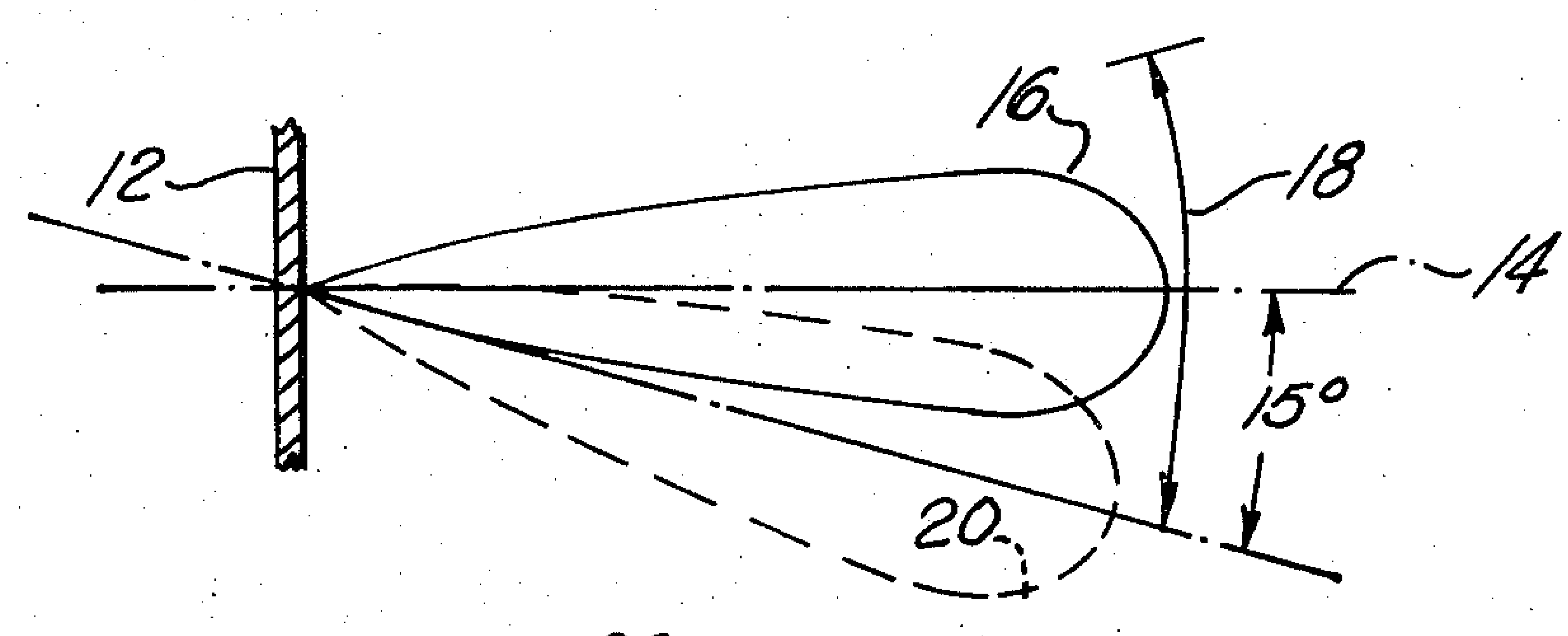


FIG. 1

FIG. 2



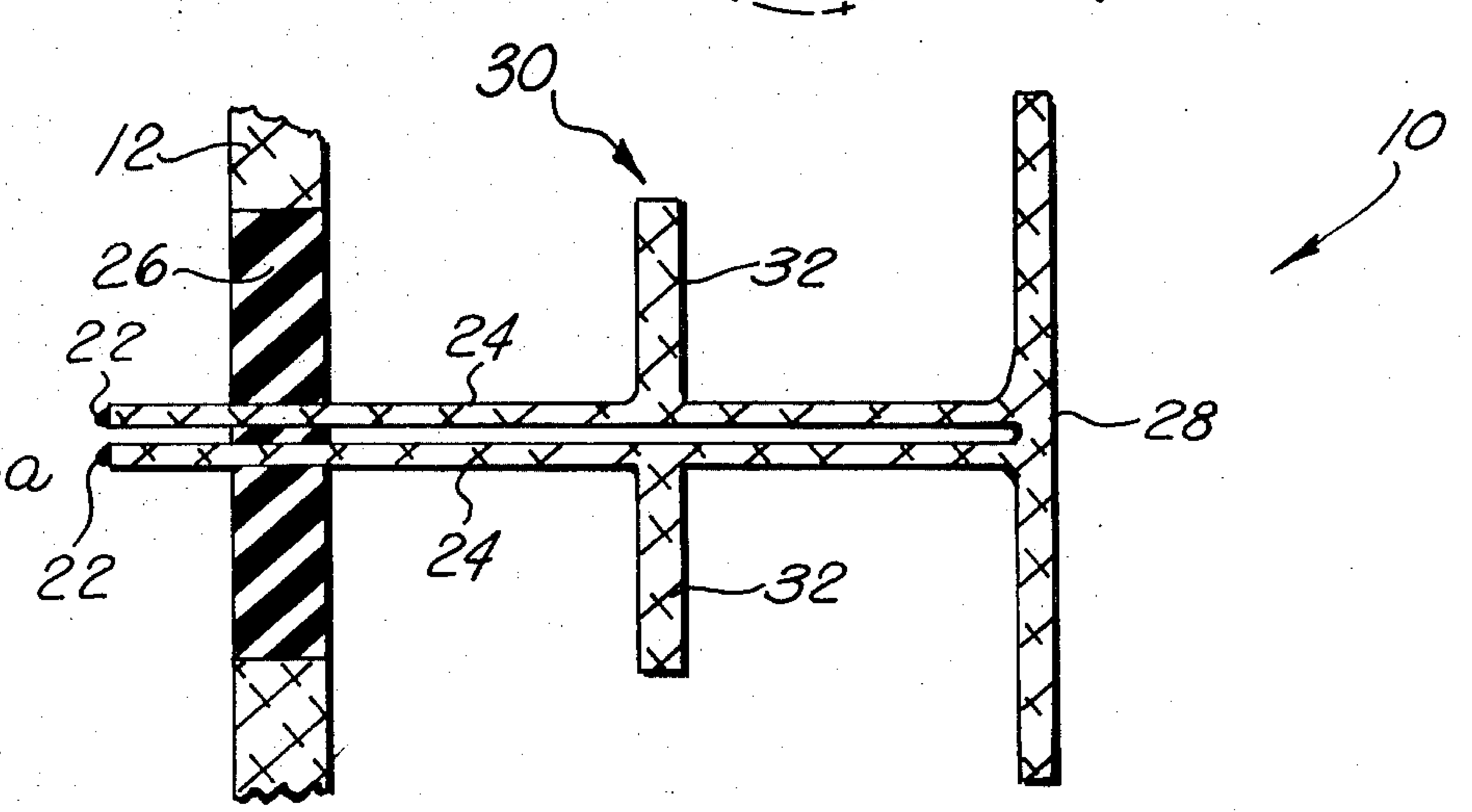


FIG. 4a

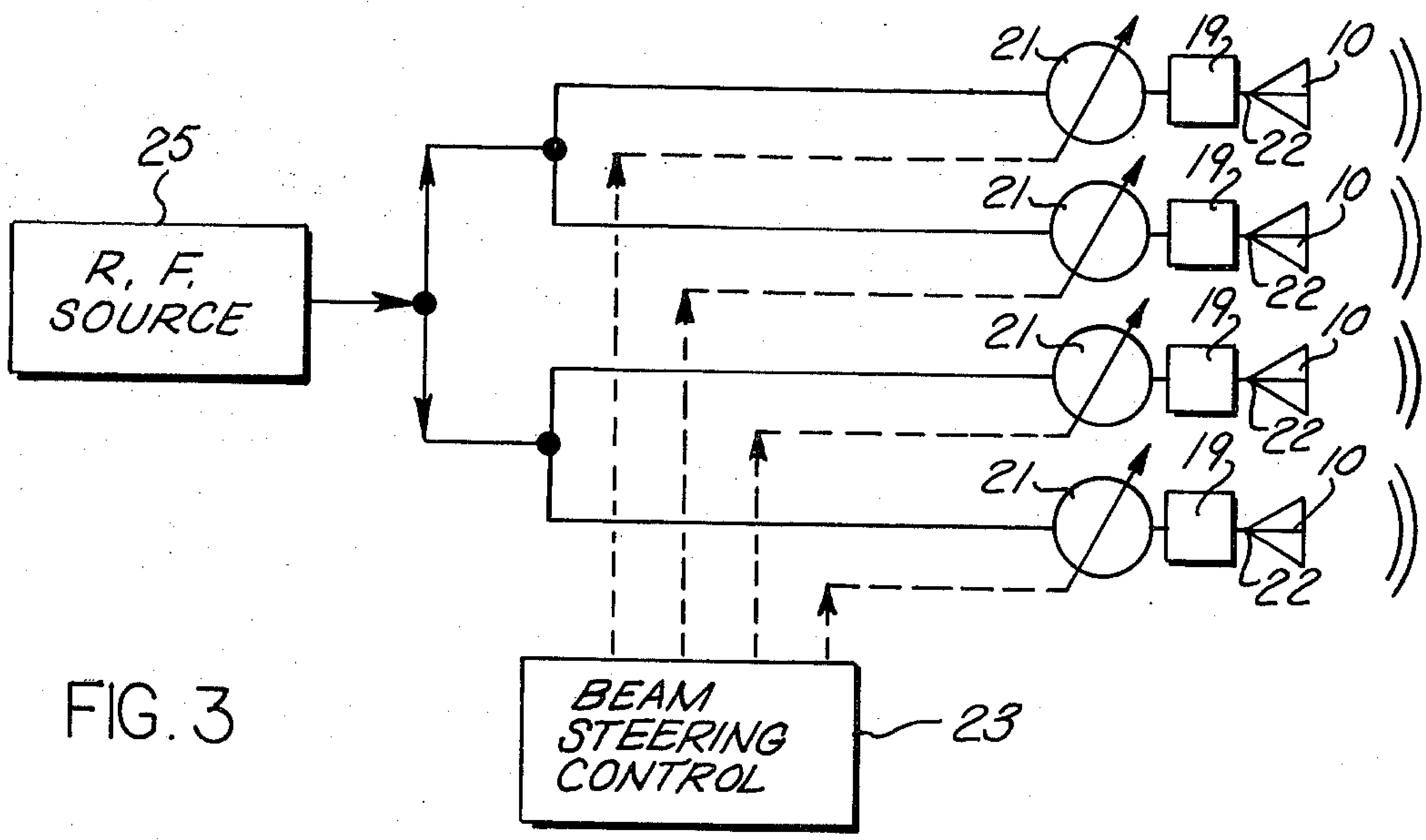


FIG. 3

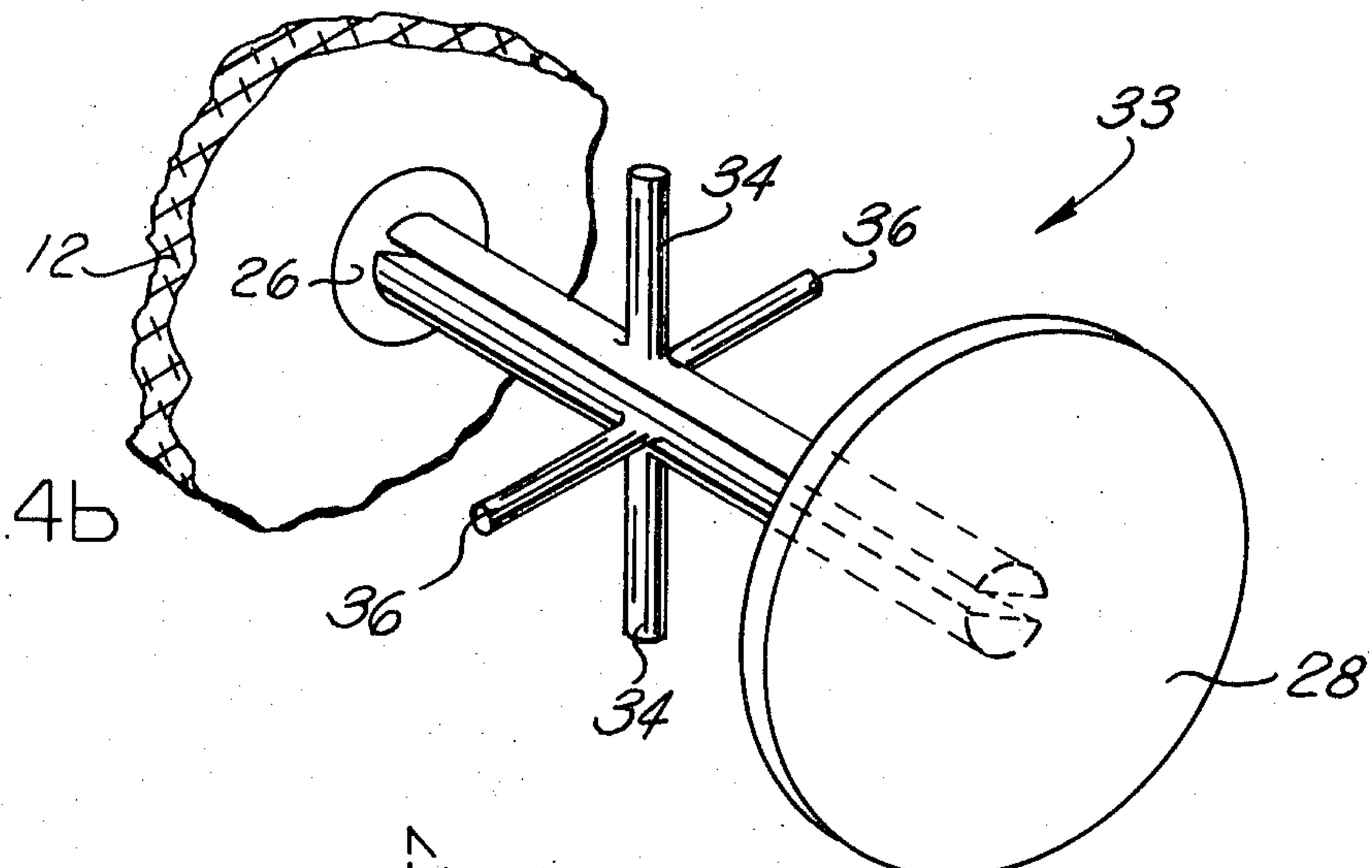


FIG. 4b

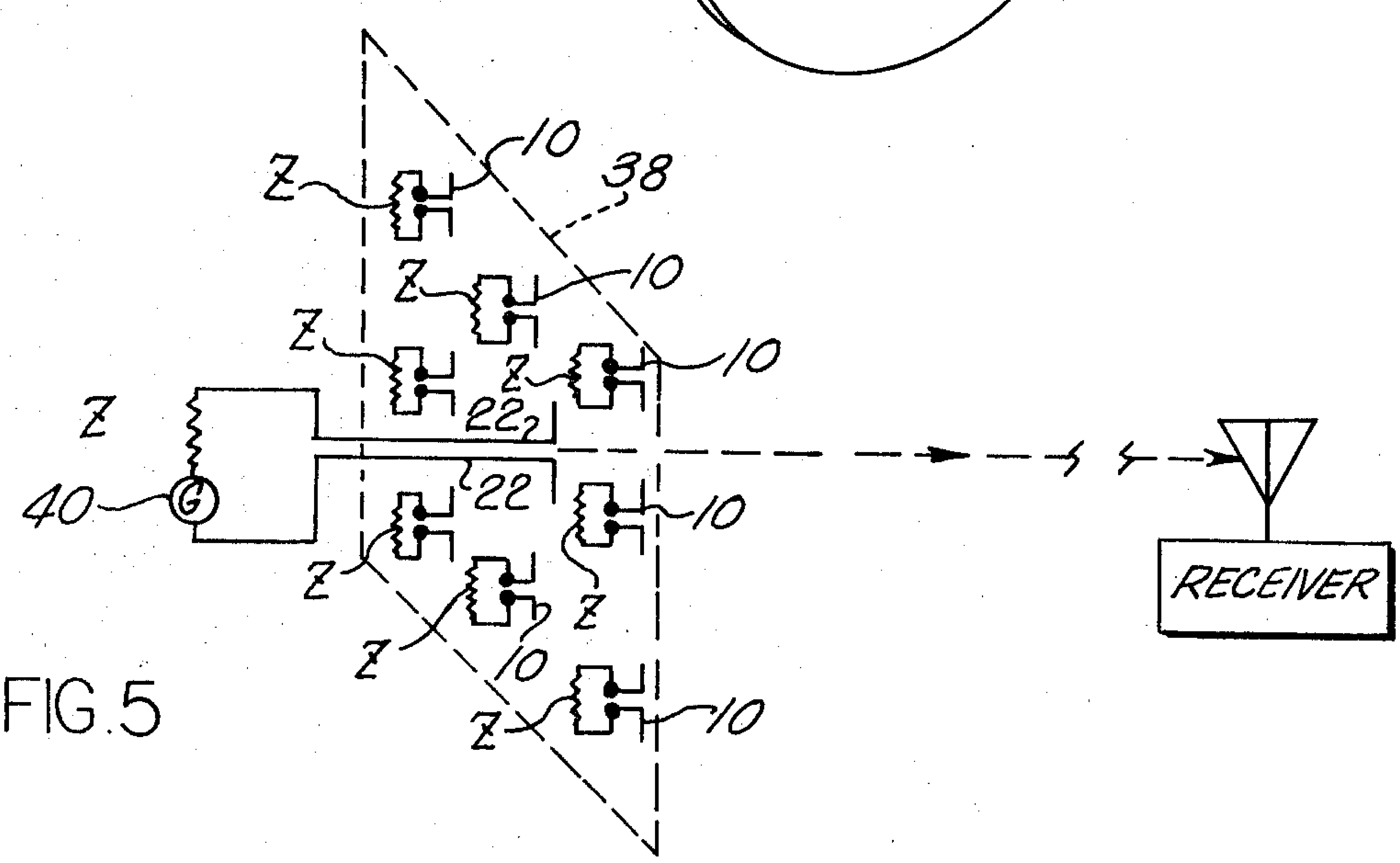


FIG. 5

FIG. 6

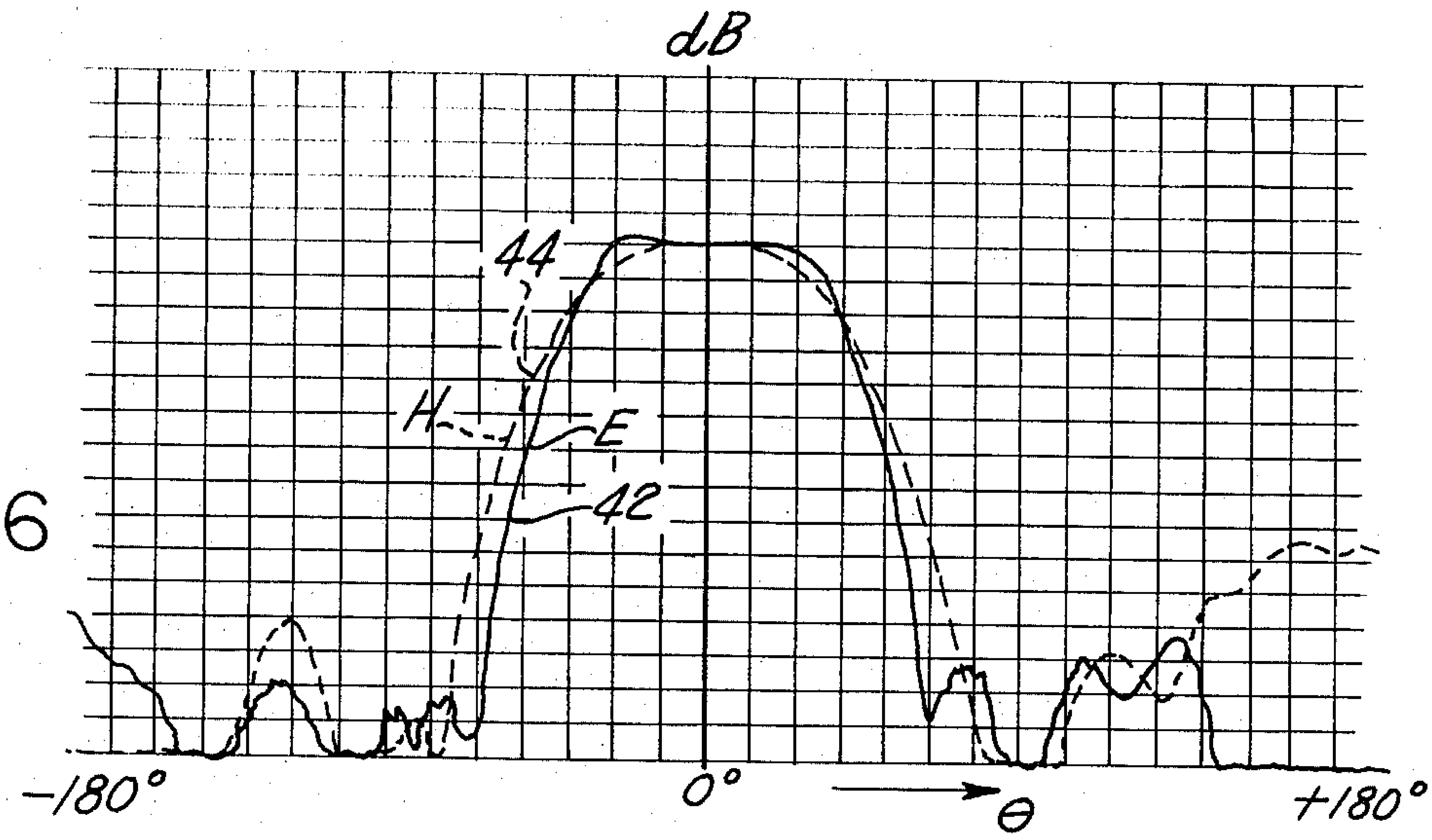


FIG. 7

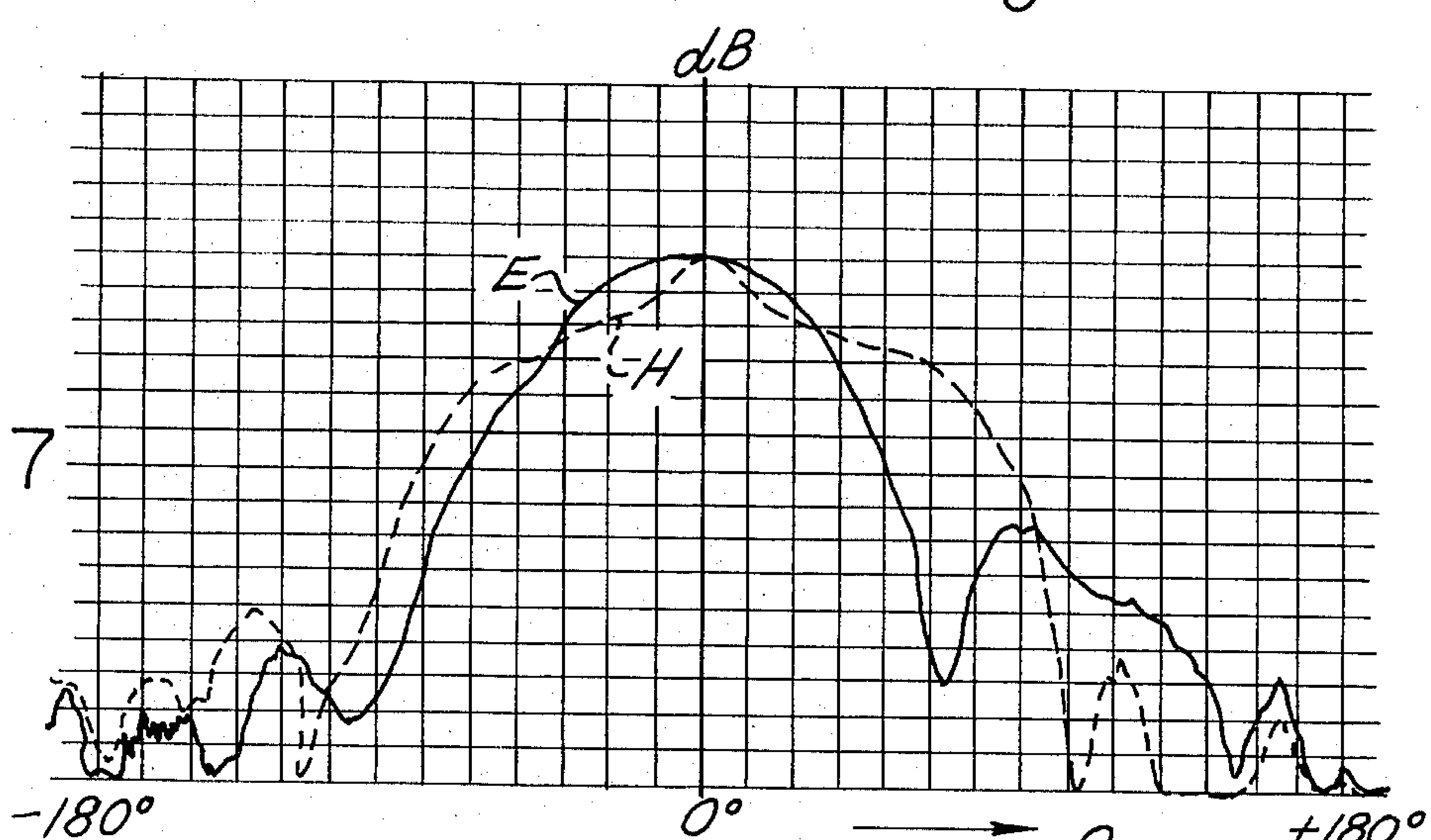
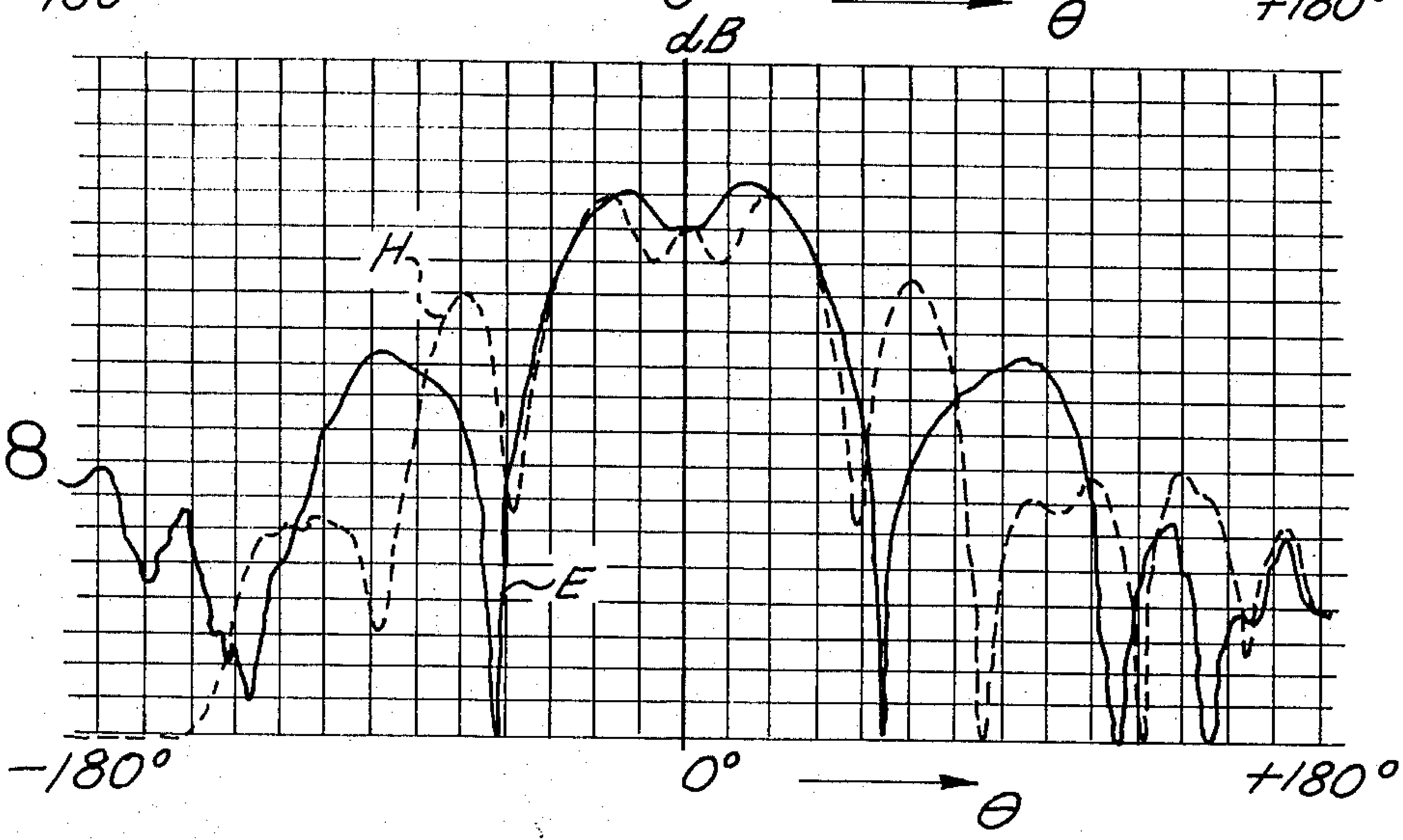


FIG. 8



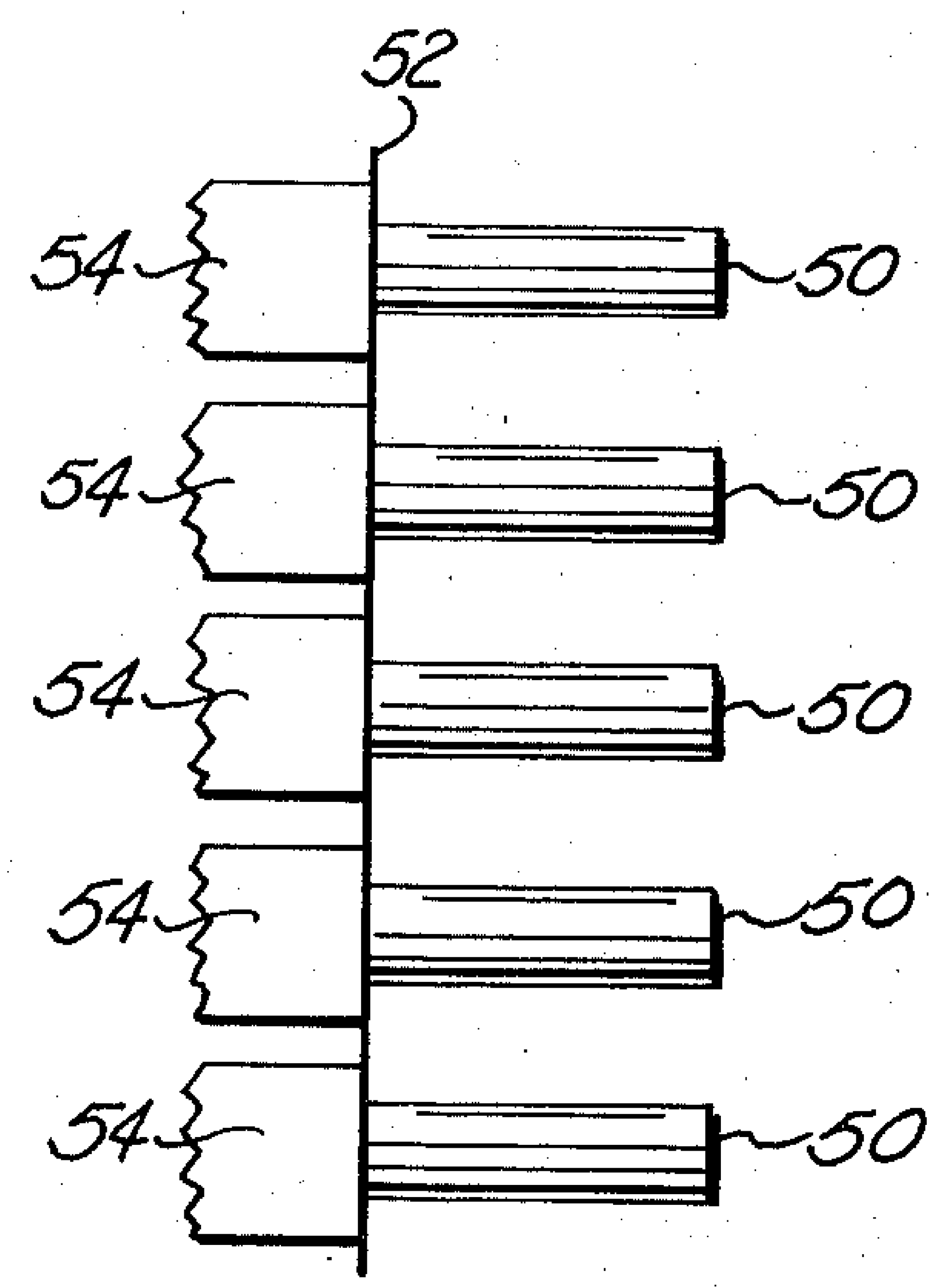


FIG. 9a

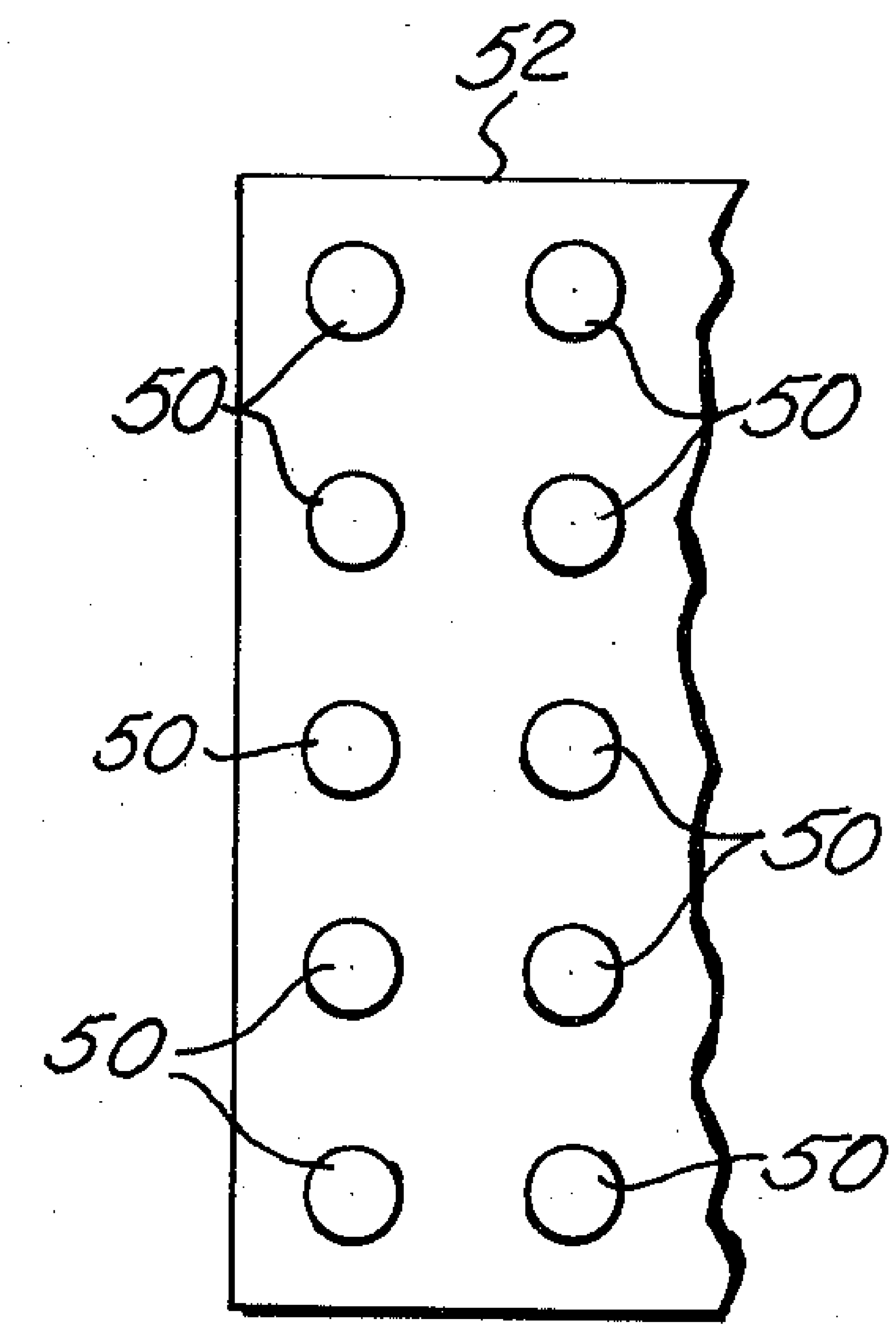


FIG. 9b

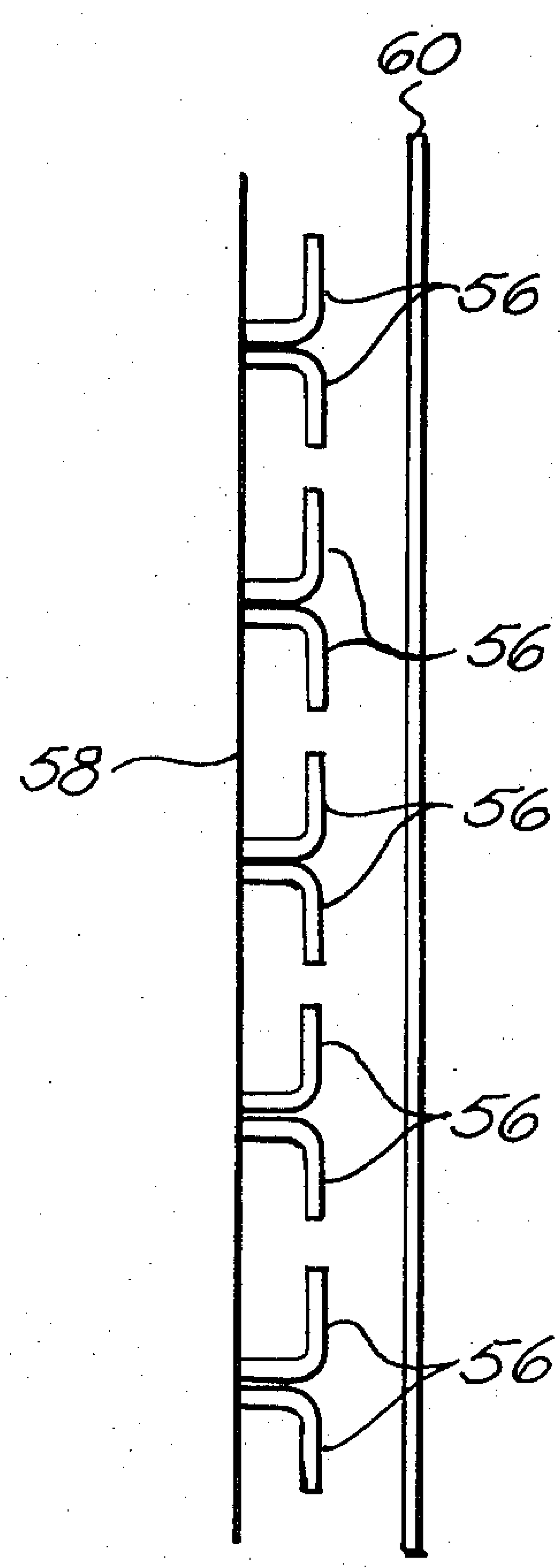


FIG. 9c

LIMITED SCAN ANTENNA ARRAY

BACKGROUND OF THE INVENTION

The far-field radiation pattern of an antenna array is the sum of contributions of each of the element antennas which constitute the array, with the relative phases of the contributions in the far field being taken into account in the summation. Under certain circumstances, an antenna array pattern may be represented as a product of an array factor and an element pattern. The required circumstances are that the elements be identical, that their generator impedances be identical, that the mutal energy interaction between each element and its neighboring elements extend over a region which is small compared with the over-all size of the array so that edge effects are relatively small, and that the elements other than those at the edges all see almost the same environment of neighboring elements, as would be the case when the elements are uniformly spaced on a plane.

The array factor describes an antenna pattern which would be produced by a hypothetical antenna array consisting of isotropically radiating antenna elements whose phase centers are located at the phase centers of the elements of the actual array.

The element pattern to be employed in representing the actual array pattern as a product of an array factor and an element pattern, is the element pattern which would be exhibited by an actual element antenna when it is located in its array environment. Such an element pattern may be produced by exciting one element antenna when it is mounted in the array, with the other element antennas not directly excited, but instead loaded at their terminals by impedances equal to the internal impedance of their inactive generators. It is well known that the element pattern which is thus obtained, hereinafter referred to as the element-in-array pattern, is in general quite different from a pattern which would be produced by the same element antenna mounted alone on a ground plane. The differences are due to parasitic excitation of elements which surround the directly excited element. The neighboring elements are excited by energy coupled to them through mutual impedances and paths which exist among them and the directly excited element. A part of the energy thus coupled to the neighboring elements is radiated to the far field and combines with energy radiated from the directly excited element to produce the element-in-array pattern. This pattern is, of course, dependent upon the coupling parameters between the element antennas as they are located in the array as well as upon the characteristics which a single element would have if standing alone.

When the principle beam of an array is steered off the array's normal mechanical axis by changing the relative phases of excitation of the element antennas, only the array factor is steered in space. The element-in-array pattern is not steered nor altered appreciably when the steering covers relatively small angles. Thus the element-in-array pattern is stationary in space during steering, and the array factor, by which it is multiplied to arrive at the resultant actual array pattern, is offset angularly so that the tip of the central lobe of the array pattern appears to describe approximately the contour of the element-in-array pattern when the array factor is steered progressively farther off the mechanical axis. The amplitude of the central or principal lobe

of the array factor is relatively constant as the antenna beam is steered off axis by small angles; it is diminished only in proportion to the consine of the steering angle, the cosine effect resulting from a foreshortening of the array when projected at the small angle steered off axis.

For many applications in which the beam must be steered over an angular range centered at the mechanical axis, an ideal element-in-array pattern would be one whose shape exactly compensates for the minor cosine reduction of the array factor so that the resulting pattern would have uniform sensitivity for all steering angles within the range. Beyond the steering range, the element-in-array pattern would ideally be zero so that sidelobes and grating lobes would be suppressed. Each sidelobe of the array pattern is created mainly by only a small percentage of the elements of the array. The grating lobes are those other than the principal lobe which are produced by concerted phase action of a great number of the elements. Grating lobes may arise at angles of the array pattern for which the path lengths of energy contributions from neighboring elements differ by an integral multiple of a wavelength.

SUMMARY OF THE INVENTION

In the present invention, antenna elements are arrayed on a uniformly spaced grid in a plane. The dimensions of the antenna elements themselves are selected in such a way as to control the mutal electromagnetic coupling between elements so that the element-in-array pattern approaches the ideal element-in-array pattern for antenna arrays which are to be steered electronically over small angles. That is, the mutual coupling is controlled to provide an element-in-array pattern having a main lobe with a nearly flat top across the scanning range and having rapidly decreasing sides outside of that range and having low sidelobes and low pattern values at the angles where grating lobes could occur.

One or more structural elements such as a thin dielectric sheet may be used also to control mutual energy transfer laterally among elements of the array.

Accordingly, one object of the present invention is to provide an antenna array which has nearly equal gain everywhere within an angular region over which it is capable of being electronically steered.

Another object of the invention is to provide an antenna array whose characteristics are controlled to have relatively high and uniform gain over a steering range, low side lobes, and low grating lobes, by controlling the electromagnetic energy coupling among element antennas of the array.

Another object of the invention is to provide an array whose elements have an element-in-array pattern with a substantially constant sensitive over a central angular range and a very rapid reduction in sensitivity from the central range to more remote angular ranges and very low sensitivity in more remote ranges.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a high-gain broadside antenna array.

FIG. 2 shows a principal lobe of the array in polar coordinates, and its beam steering range.

FIG. 3 is a block diagram of a conventional electronic beam steering system.

FIG. 4*a* is a diagram of the construction of an element antenna for a preferred embodiment of the invention for linear wave polarization.

FIG. 4*b* shows the construction of an element antenna for circular wave polarization.

FIG. 5 shows an arrangement for measuring an element-in-array pattern of an element antenna.

FIG. 6 depicts two element-in-array patterns of an element antenna in which a disk member has a diameter which is correct.

FIG. 7 shows two element-in-array patterns of the element antenna of FIG. 6, but in which the disk member has a diameter which is too small.

FIG. 8 shows two element-in-array patterns of the element antenna of FIG. 6, but in which the disk member has a diameter which is too large.

FIG. 9*a* shows a side view of an embodiment in which the element antennas are dielectric rods.

FIG. 9*b* is a front view of a portion of the array of FIG. 9*a*.

FIG. 9*c* is a side view of yet another embodiment in which the element antennas are dipoles whose mutal energy coupling is determined in part by a dielectric sheet that covers them.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In a preferred embodiment of the invention, a number of element antennas **10** are arrayed over a ground plane **12** at the intersections of a uniformly spaced grid as shown in FIG. **1**. The spacing between rows and columns of elements **10** is in the range of 0.75 to 1.10 wavelengths such as 0.85 wavelengths for the frequency of excitation employed. A principal mechanical axis **14** of the antenna is perpendicular to the plane of the array **12** as shown in FIG. **2**, and defines the direction of the center of a principal lobe **16** of a resultant antenna array pattern when all of the element antennas **10** are excited with equal phase. The principal lobe **16** of the resultant array pattern may be steered over an angular range **18** centered on the mechanical axis **14**, by linear phasing of the element antennas **10** relative to each other depending upon their positions. In the preferred embodiment described herein, steering may be accomplished over a range **18** extending to an outer limit in any direction from the mechanical axis **14**, the outer limit being in a range 0° to at least 15°. In FIG. **2**, the principal lobe **16** of the resultant array pattern is shown in polar coordinate form for the condition when the principal lobe is located on the mechanical axis, and is shown as a dotted line **20** for a steering position 15° off the axis.

Each element antenna **10** is mounted on the common ground plane **12** and in this embodiment is fed from behind the ground plane **12** at element antenna terminals **22** through any suitable baluns known in the prior art. To simplify the description of this invention, a conventional electronic beam steering control system is employed, as shown in FIG. **3**. Each balun **19** is driven by a phase shifter **21** which can be typically of a conventional diode switching type controllable by DC potentials applied to the diodes of the phase shifter **21** by a beam steering control circuit **23**. The phase shifters **21** are excited by a corporate feed system from a source **25**.

All of the element antennas **10** of the array are identical. The element antennas **10** in the preferred embodiment are similar to short backfire antennas except for the selection of their dimensions. The dimensions in the present invention are determined empirically. In FIG. 4*a* an element antenna **10** is shown for radiating an electromagnetic wave of one linear polarization.

Each element antenna **10** comprises two poles or transmission members **24** connected to the input terminal **22** and mounted perpendicularly to the ground plane **12**. An insulator **26** prevents the ground plane **12** from short-circuiting the element. The transmission members **24** are between 0.4 and 0.6 wavelength long and are connected to a conductive disk **28** at their ends remote from the ground plane. The disk **28** has a diameter in the range of 0.38 to 0.62 wavelength. If desired, the transmission members **24** may be electrically connected together either instead or in addition by a capacitor whose position on the transmission members **24** with respect to the terminating disk **28** may be adjusted. Approximately midway between the ground plane **12** and the terminating disk **28** on the transmission members **24**, a radiating dipole **30** is mounted. One arm of the dipole **30** is mounted on each of the transmission members **24**, each arm **32** being approximately one-fourth wavelength long. When the antenna element **10** is excited, current flows from the terminals **22** along the transmission members **24** to the dipole **30** and out along the dipole arm **32** to their ends where it is continuously reflected as is well known in the prior art. The current in the dipole arms **32** together with the voltage established between the two dipole arms creates standing waves of electromagnetic fields between the ground plane **12** and the terminating disk **28** of the element antenna **10**. The ground plane **12** and the terminating disk **28** serve as ends of a rather loosely bounded cavity, centered on the transmission members **24**, which resonates under the stimulation of the dipole **30**. Electromagnetic energy easily escapes from the cavity and is radiated past the edges of the terminating disk **28** in a direction generally broadside to the ground plane **12**. At the same time, the rapidly alternating electric and magnetic fields in the region around the element antenna **10** excite current flow in the other element antennas **10** near the directly excited element antenna principally by capacitive and magnetic induction, it is believed. Because all of the elements **10** of the array are excited directly at their terminals during normal operation, the particular element whose structure and operation are being described in parasitically excited in like manner by the neighboring elements so that the far-field radiation from every element has a parasitically excited component as well as a component due to direct excitation.

Shown in FIG. 4*b* is an alternative form **33** of element antenna suitable for radiating circularly polarized waves. Element **33** has two pairs of dipole arms **34, 36** which can be excited with 90° phase displacement between their exciting currents to produce waves of circular, elliptical or linear polarization. The phase displacement required between their currents for circular or elliptical polarization can be achieved by selecting the lengths of the two pairs of dipole elements so that they have reactive impedances of opposite signs.

All of the elements **10** contribute to the resultant array pattern in the far field; the contribution which is due to excitation energy originally entering the array at the terminals **22** of one particular element antenna **10** produces an element-in-array pattern of one element. In order that the nature of the element-in-array pattern be clear, a circuit for measuring it approximately is shown in FIG. **5**. In FIG. **5**, nine element antennas **10** are shown arranged broadside on a grid which represents a portion **38** of the entire ground plane as marked with dotted lines on FIG. **1**. The center element of the group of elements **10** in FIG. **5** is shown being excited by a generator **40** which has an internal impedance Z. Each of the other eight elements **10** which are the nearest neighbors of the directly excited element, is terminated in the same impedance Z, which represents the internal impedance of its own presently inactive generator. The exciting voltage is zero for all except the center element whose element-in-array pattern is to be measured. Radiation patterns measured in the far field under these conditions are the element-in-array patterns of an element antenna **10** if the element-in-array pattern is significantly influenced only by the nearest neighbors. A more precise element-in-array pattern could be measured by including more element antennas farther out in the array, also passively terminated in impedance Z.

A set of measured element-in-array patterns of an element **10** employed in the preferred embodiment is shown in FIG. **6** on rectangular coordinates. The element that produced the patterns of FIG. **6** was in a 7 × 7 array over a ground screen. Curves **42, 44,** are principal E-plane and H-plane element-in-array patterns respectively. It should be noted that portions of the E-plane and H-plane patterns **42, 44** within ± 15° about the 0° mechanical axis have almost constant strength. The patterns decline slowly from 15° to 30° off axis and thereafter fall more rapidly to levels of less than 18 dB below the crest of the main lobe.

The desired flat-top shapes, well within ± 0.5 decibels, of the element-in-array patterns **42, 44** are achieved in the preferred embodiment with lengths of 0.5 wavelength for the transmission members **24**, a terminating disk **28** diameter of 0.405 wavelength, a dipole **30** length from the unsupported end of one dipole arm **32** to the unsupported end of the other arm **32** of 0.45 wavelength, and with the dipole arms located 0.25 wavelength from the screen and from the disk **28**. The spacing between element antennas is 0.85 wavelength, on a square grid. These dimensions produce appropriate values of partial capacitance from the terminating disk to the terminating disks of neighboring antennas and to the ground plane, and produce appropriate self and mutual inductances, capacitances, and energy transmission parallel to the ground plane to shape the element-in-array pattern to a flat-topped, steep-sided shape which is desired, as shown in FIG. **6**.

The proper dimensions of various structural members of the element antennas depends upon the dimensions selected for other structural members of the same element. The disk **28** can have diameters between 0.25 and 0.60 wavelength. The disk can be located between 0.4 and 0.6 wavelengths from the main reflector. Spacings between elements ordinarily range from 0.75 to 1.1 wavelength.

FIGS. **7** and **8** show element-in-array patterns obtained under conditions similar to those of FIG. **6**, except with incorrect diameters of the terminating disks **28**. The patterns of FIG. **7** are for a terminating disk diameter of 0.275, which is too small, and the patterns are not flat-topped. The patterns of FIG. **8** are for a terminating disk diameter of 0.475, which is too large, and the patterns therefrom are not flat-topped either.

To obtain the resultant far-field pattern of the antenna array, the element-in-array pattern **42** is multiplied at every value of angle on the abscissa of FIG. **6** by the value of an array factor at the same angle, as was discussed above. The array factor employed must correspond to the steering angle for which a pattern is sought.

While the energy transferred between elements of the array is relatively low for the type of antenna element described in the preferred embodiment, it is nevertheless significant and great enough to be manipulated as was described herein to shape the element-in-array pattern to achieve the desired array performance.

It can be seen in FIG. **6** that resultant patterns of the array will have a principal lobe whose maximum value is almost as great for a beam steering angle of 15° as it is for a steering angle of 0°; the maximum value is smooth between those angles. This is a very desirable result for many applications of steerable arrays; one advantage is that it minimizes amplitude-modulation of the sensitivity of the array as a function of beam steering angle.

While the antenna array has been described in terms of antenna elements of a particular type resembling a short backfire antenna, and although specific dimensions of the element antenna of the preferred embodiment have been recited in the interest of providing a specific example, the invention may be practiced by any of a variety of element antennas in array, provided only that their structure makes them amenable to appropriate tailoring of the complex mutual energy coupling from an element to its neighbors when in array, and provided that a particular pattern shape which is desired is one of the element-in-array patterns which are achievable by manipulation of the dimensional parameters of the element antenna and of spacing between element centers.

An example of an embodiment employing dielectric rod element antennas is shown in FIGS. **9***a* and **9***b*. Dielectric rods **50** are arranged on a grid spacing over a ground screen **52**, and are fed by waveguides **54** from an array feed network. The diameter and length of a rod **50** affects the energy coupled transversely to neighboring rods **50**, to shape an element-in-array pattern.

Another embodiment, shown in FIG. **9***c*, utilizes half-wave dipole element antennas **56** supported near a ground plane **58**, and has a thin dielectric sheet **60** covering the entire array. The dielectric sheet has a relative dielectric constant of about 10, and is strongly affects the amount and phase of energy coupled laterally among the dipole element antennas, to shape the element-in-array pattern.

It is not necessary that the element antennas be located at the intersections of a square grid as was described in the preferred embodiment. The principal requirement upon the placement of element antennas is that all of the antennas except the ones near the edge should have the same values of complex mutual coupling with respect to the element antennas surrounding them.

Although the invention has been described above in transmitting-antenna terms it is also suitable by reciprocity for use as a receiving antenna, or for both transmitting and receiving.

What is claimed is:

1. A planar phase-steerable antenna array having an axis perpendicular to the array and having a main lobe whose direction is steerable by phase control over a region extending from the axis to an outer limit ranging from 0° to 25° off the axis comprising a phase-controlled energy feed system, element antennas arranged substantially in a plane with uniform spacing in a spacing range between 0.75 to 1.10 wavelength, each of said element antennas comprising feed terminals for accepting excitation energy from the feed system, means having a feed-terminal end and a second end for conducting of said excitation energy from the feed terminals in a direction substantially parallel to the axis, a substantially planar main reflector nearer to the feed-terminal end of the conduction means than to the second end and parallel to the array plane for reflecting electromagnetic waves, a subreflector located at the second end of the conduction means and at a distance from the main reflector in a range of distances of 0.4 to 0.6 wavelength for reflecting electromagnetic waves, said subreflector having overall size parallel to the array in a range of 0.25 to 0.60 wavelength, electromagnetic radiation means connected to the conduction means between the main reflector and the subreflector and excited by energy conducted by the conduction means thereto for producing electromagnetic fields, the precise dimensions for said uniform spacing of the element antennas and for said distance of the subreflector from the main reflector and for said over-all size of the subreflector parallel to the array being chosen so as to provide an element-in-array pattern having a level that is uniform within ±0.5 decibel everywhere within ±15° of the direction of the main lobe and having a sidelobe level at least 18 decibels below the main lobe level everywhere beyond ±85° from the direction of the main lobe.

2. A planar phase-steerable antenna array as defined in claim **1** wherein said means for conduction comprises open-wire transmission line means extending from said terminals to said subreflector, and said main reflector comprises a conductive ground plane substantially continuous across the array, and said subreflector comprises a conductive plate, and said electromagnetic radiation means comprises half-wave dipole means connected approximately midway between the main reflector and the subreflector.

3. A planar phase-steerable antenna array as defined in claim **2** wherein said uniform spacing of the element antennas is approximately 0.85 wavelength, said distance of the subreflector from the main reflector is approximately 0.5 wavelength, and said conductive plate is a disk having a diameter of approximately 0.41 wavelength.

4. A planar phase-steerable antenna array having gain and comprising a plurality of element antennas arranged generally in a plane with the element antennas being uniformly spaced apart from each other in directions parallel to said plane by a distance in a range from approximately 0.75 to 1.10 wavelength and having terminals, electronic beam-steering means for controlling the direction of a main beam of said array over a range of ± 15° from an array mechanical axis, said beam steering means comprising phase-controlled excitation means connected to the terminals of the element antennas for exciting the element antennas with power, said element antennas each comprising a partial reflector and a main reflector substantially larger than the partial reflector, with all of the partial reflectors being located in a common plane and all of the main reflectors being located in a second common plane, means for conducting the power from said terminals along a path from the main reflector toward the partial reflector, and electromagnetic radiation means interposed between the main and partial reflectors and connected to receive power from the conduction means for producing electromagnetic waves between the main and partial reflectors.

5. A planar phase-steerable antenna array as set forth in claim **4** wherein said element antennas are spaced apart about 0.85 wavelength, said main and partial reflectors are spaced apart about 0.5 wavelength, said electromagnetic radiation means interposed between the main and partial reflectors comprises a half wave dipole interposed approximately midway between each of said main and partial reflectors, and each of said partial reflectors comprises a disk having a diameter of about 0.41 wavelength, whereby the energy coupling among element antennas has values such that, for steering directions within said range of ±15°, the gain of the array is degraded by less than 1 decibel and the maximum sidelobe level for regions 85° and farther from the main beam is below −20 decibels referred to the main beam.

6. A planar phase-steerable antenna array having an axis, comprising a plurality of equally spaced element antennas in a plane, each of said element antennas comprising structural member means having at least one dimension for determining mutual energy coupling of the element antenna with others of said element antennas in the array, said dimension being proportioned to produce an element-in-array radiation pattern flat-topped with ±0.5 decibel everywhere within ±15° of the axis of said element-in-array pattern, energizing means for feeding phase-controlled excitation power to said elements for radiating an electromagnetic beam steerable within an angle of at least ± 15 from said axis, each of said element antennas cocmprises feed terminals for accepting excitation power from the energizing means, means having a feed-terminal end and a second end for conducting of said excitation power from the feed terminals in a direction substantially parallel to the axis, a substantially planar main reflector nearer to the feed-terminal end of the conduction means than to the second end and parallel to the array plane for reflecting electromagnetic waves, and wherein said structural member means comprises a subreflector located at the second end of the conduction means and at a distance from the main reflector in a range of distances of 0.4 to 0.6 wavelength for reflecting electromagnetic waves.

7. A planar phase-steerable antenna array having an axis, comprising a plurality of equally spaced element antennas in a plane, each of said element antennas comprising structural member means having at least one dimension for determining mutual energy coupling of the element antenna with others of said element antennas in the array, said dimension being proportioned to produce an element-in-array radiation pattern flat-topped within ± 0.5 decibel everywhere within ± 15° of the axis of said element-in-array pattern, energizing means for feeding phase-controlled excitation power to said elements for radiating an electromagnetic beam steerable within an angle of at least ± 15 from said axis, each of said element antennas comprises feed terminals for accepting excitation power from the energizing means, means having a feed-terminal end and a second end for conducting of said excitation power from the feed terminals in a direction substantially parallel to the axis, a substnatially planar main reflector nearer to the feed-terminal end of the conduction means than to the second end and parallel to the array plane for reflecting electromagnetic waves, and wherein said structural member means comprises a subreflector located at the second end of the conduction means and at a distance from the main reflector in a range of distances of 0.4 to 0.6 wavelength for reflecting electromagnetic waves, said subreflector having over-all size parallel to the array in a range of 0.25 to 0.60 wavelength, electromagnetic radiation means connected to the conduction means between the main reflector and subreflector and excited by energy conducted by the conduction means thereto for producing electromagnetic fields.

8. A planar phase-steerable antenna array as defined in claim **7** wherein said means for conduction comprises open-wire transmission line means extending from said terminals to said subreflector, and said main reflector comprises a conductive ground plane substantially continuous across the array, and said subreflector comprises a conductive plate, and said electromagnetic radiation means comprises half-wave dipole means connected approximately midway between the main reflector and the subreflector.

9. A planar phase-steerable antenna array as defined in claim **8** wherein said uniform spacing of the element antennas is approximately 0.85 wavelength, said distance of the subreflector from the main reflector is approximately 0.5 wavelength, and said conductive plate is a disk having a diameter of approximately 0.41 wavelength, said diameter being one of said dimensions for determining said mutual energy coupling.

10. A method of constructing a planar phase-steerable antenna array comprising the steps of arraying a plurality of element antennas in a plane with uniform spacing therebetween, energizing a centrally located one of said element antennas with an AC power source, passively terminating all of the others of said element antennas with impedances simulating identical AC power sources, measuring far field radiation patterns of the element antenna so situated in the array environment to detect the flatness of patterns within an angular range about the axis of symmetry, progressively varying in increments at least one of the dimensions

a. spacing between element antennas
b. height of an element antenna perpendicular to the plane of the array
c. breadth of an element antenna measured parallel to the plane of the array, repeating said step of measuring the patterns to detect flatness after each increment and adjusting one of the dimensions so as to obtain the flattest pattern within said range, and replacing said impedances with AC power sources.

11. The method as defined in claim **10** wherein said step of measuring within an angular range comprises measuring within a range of at least ±15°, and wherein said step of adjusting comprises adjusting so as to obtain a pattern flat within ±0.5 decibel within said range.

12. The method as defined in claim **10** wherein said step of progressively varying in increments at least one of said dimensions comprises progressively varying said breadth of an element antenna measured parallel to the plane of the array.

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