United States Patent

Chalfin et al.

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[45] **July 25, 1972**

[54] SCANNING ANTENNA HAVING A CIRCULAR LENS WITH PERIPHERALLY SPACED LINEAR ARRAYS

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[21] Appl. No.: **792,070**

[52] **U.S. Cl.** .....343/754, 343/778, 343/854, 343/911 L

[51] **Int. Cl.** **H01q 19/06**

[58] **Field of Search** .....343/753, 754, 755, 854, 911, 343/778, 911 L

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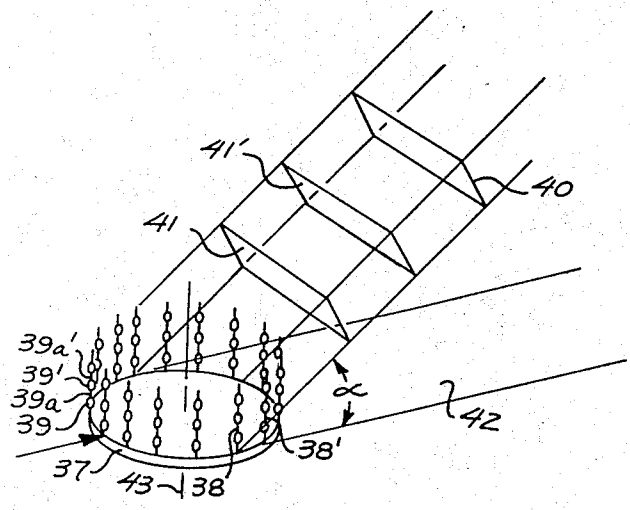
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[57] **ABSTRACT**

This disclosure relates to antenna arrays for propagating electromagnetic radiation wherein a lens, such as a geodesic or Luneberg lens, is utilized as a phase resolver of electromagnetic radiation coupled to an array of a plurality of antennas. The array of antennas is mounted to the lens in such a manner as to propagate a narrow beam of electromagnetic radiation. Preferably, phase-shift means is provided for simultaneously altering the degree of phase shift of propagated radiation between each radiating element by an incremental amount.

15 Claims, 12 Drawing Figures



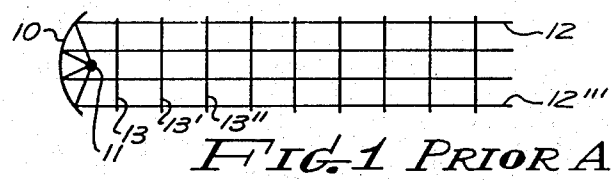


FIG. 1 PRIOR ART

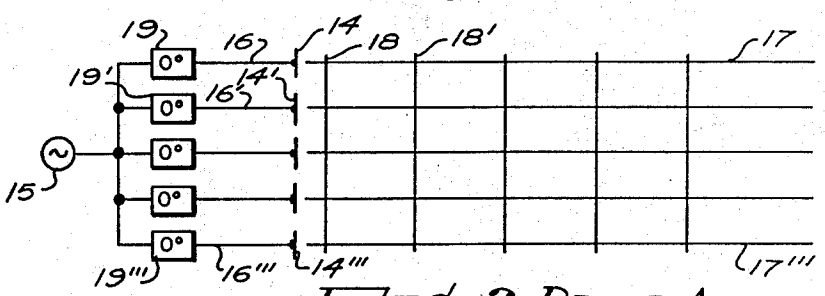


FIG. 2 PRIOR ART

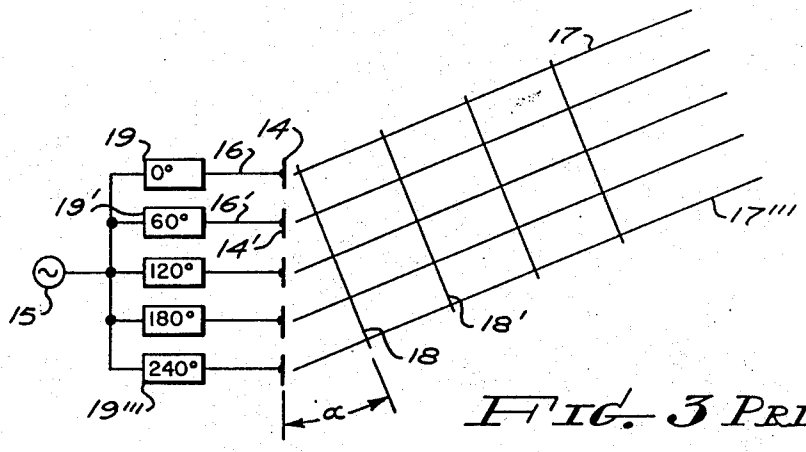


FIG. 3 PRIOR ART

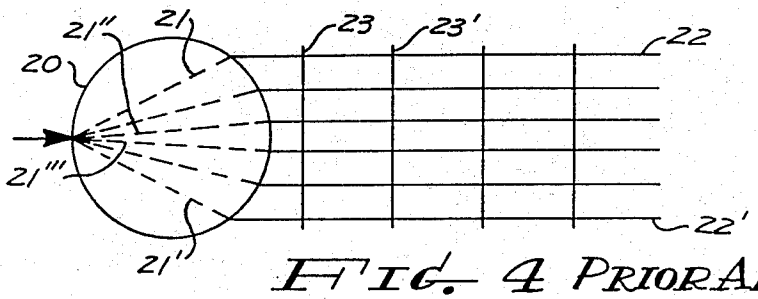


FIG. 4 PRIOR ART

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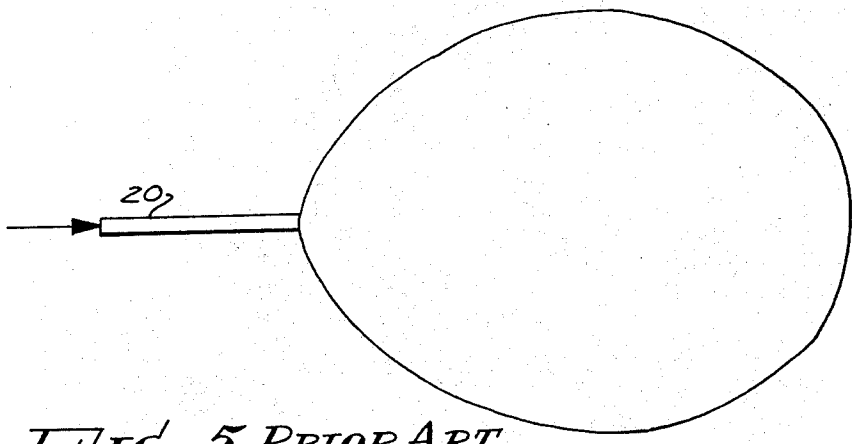


FIG. 5 PRIOR ART

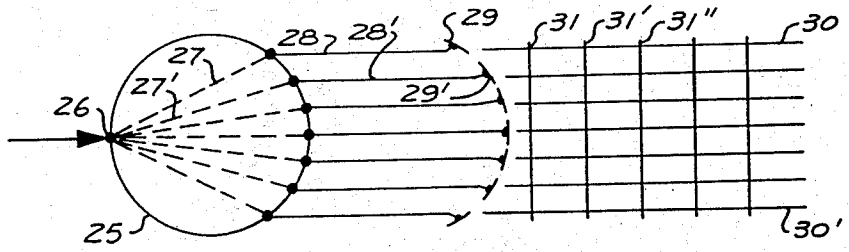


FIG. 6

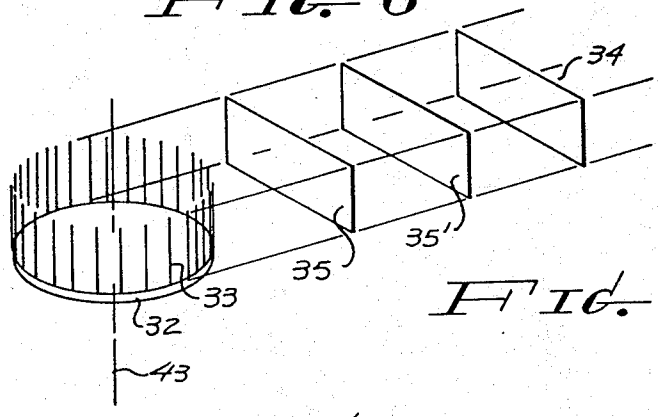


FIG. 7

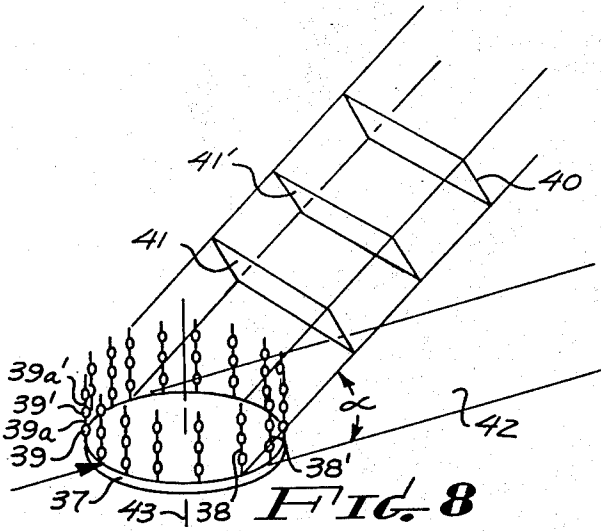


FIG. 8

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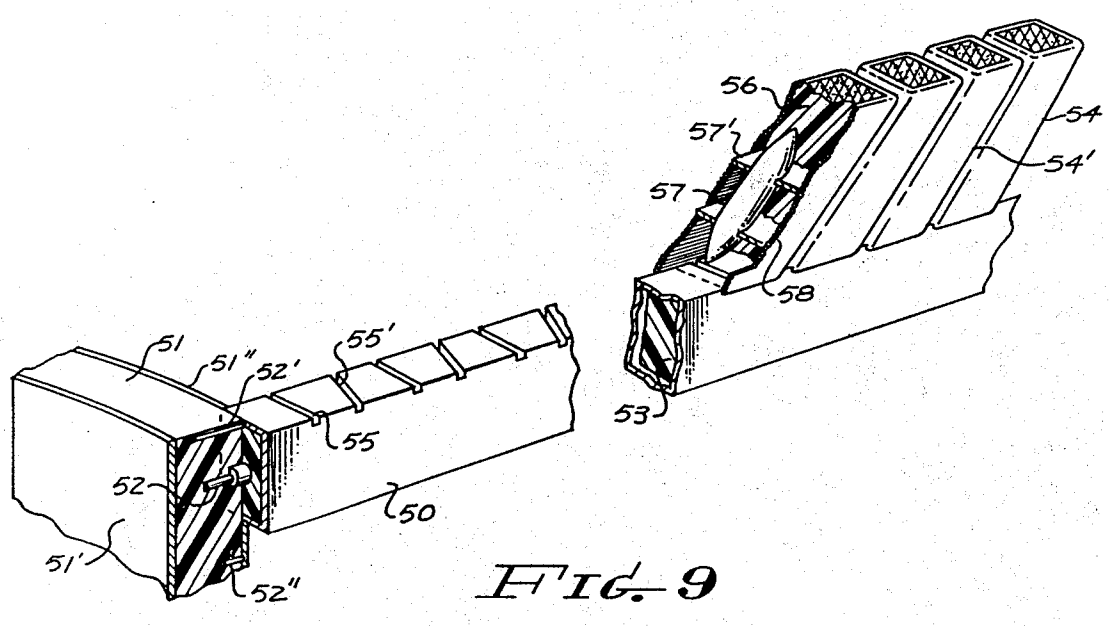


FIG. 9

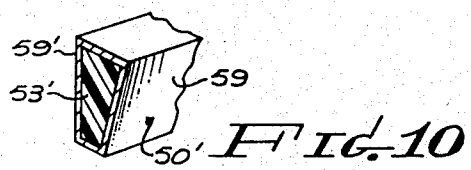


FIG. 10

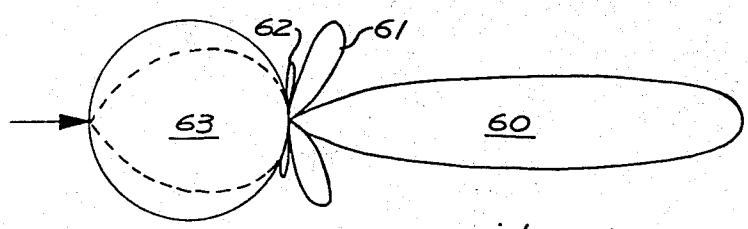


FIG. 11

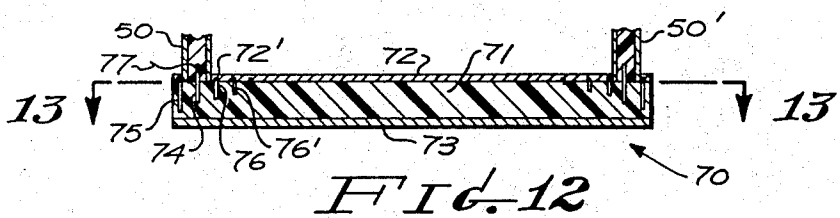


FIG. 12

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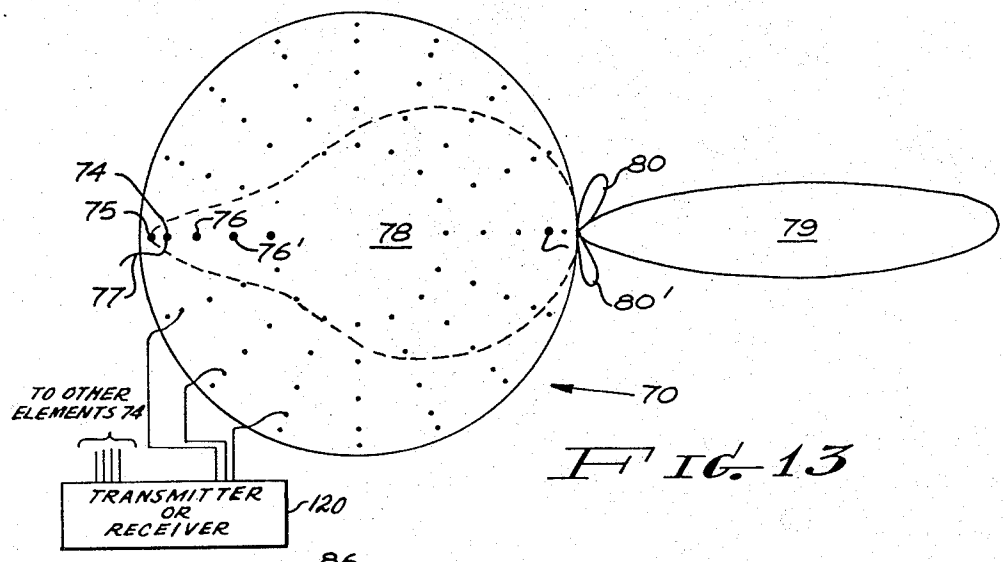


FIG. 13

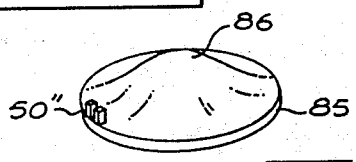


FIG. 14

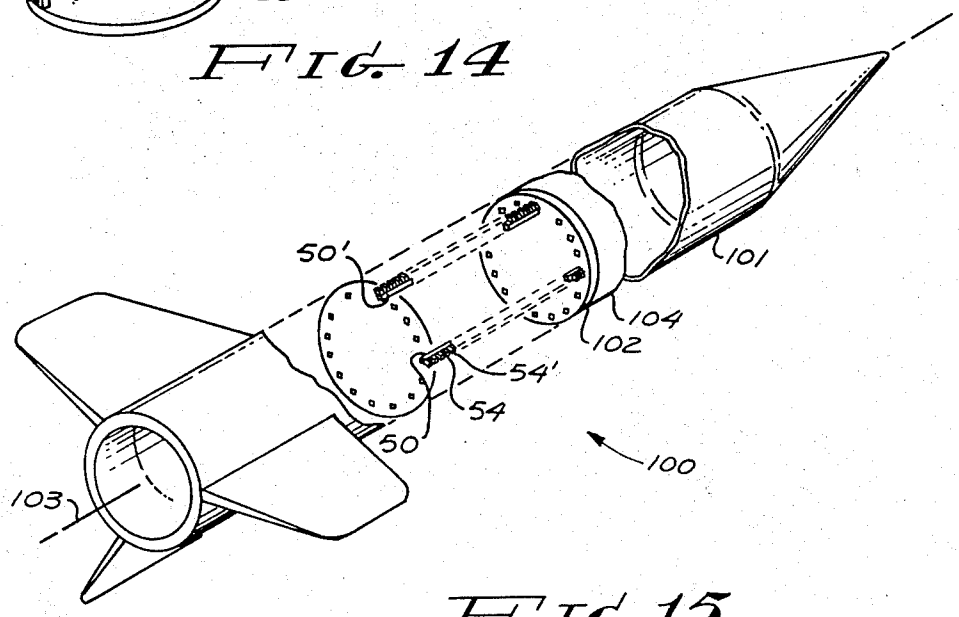


FIG. 15

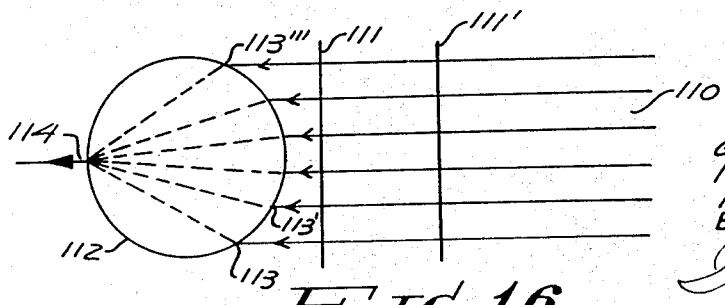


FIG. 16

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SCANNING ANTENNA HAVING A CIRCULAR LENS WITH PERIPHERALLY SPACED LINEAR ARRAYS

This invention relates to antenna arrays, and particularly to antenna arrays for propagating narrow-beam electromagnetic radiation.

Heretofore, narrow-beam electromagnetic radiation having linear or planar phase fronts has ordinarily been propagated by means of parabolic antennas or by linear arrays of dipole antennas. Parabolic antennas, although generally capable of propagating pencil beams of radiation, are ordinarily too slow to rotate due to their mechanical characteristics so that they are not able to scan rapidly enough for certain applications, such as tracking missiles. Linear and planar arrays are capable of rapidly scanning by electrically changing the phase relationships between each propagating element of the array. However, such arrays have been difficult to control so as to maintain the coplanar properties of the propagated beam. Complex, and often expensive, phase control apparatus have been used for controlling the phase relationship of each antenna, but these have not proved to be entirely satisfactory. Furthermore, it is difficult with some linear and planar arrays to scan wide areas.

It is an object of the present invention to provide an antenna array capable of an area scan.

Another object of the present invention is to provide an antenna array capable of rapidly scanning an area.

Another object of the present invention is to provide an antenna array comprising a plurality of antennas driven by means of a lens which resolves phase of the electromagnetic radiation so that the propagated beam contains coplanar phase fronts.

An antenna array according to the present invention comprises a plurality of antenna means mounted to the rim of a lens, such as a Luneberg or geodesic lens. The lens is rim fed and operates to resolve electromagnetic radiation within the lens so that the antenna means propagate a narrow electromagnetic radiation beam.

According to an optional and desirable feature of the present invention, the antenna array may be utilized for receiving electromagnetic radiation and for determining the direction from which such radiation had arrived.

According to another optional and desirable feature, each antenna means comprises a linear array of antenna elements each mounted to the lens, whereby the plurality of linear arrays propagate a narrow beam of electromagnetic radiation.

According to another optional desirable feature of the present invention, each linear array comprises supporting waveguide mounted parallel to the axis of the lens, and a plurality of antennas elements mounting to each waveguide. Phase shift means is associated with each antenna element so as to shift the phase of the propagated wave from the particular antenna by an incremental amount from the previous antenna element. This arrangement permits rapid scanning in the plane of the axis of the lens so that the beam may be propagated at any angle to the axis of the lens.

The above and other features of this invention will be more fully understood from the following detailed description and the accompanying drawings, in which:

FIG. 1 is an illustration of a typical parabolic antenna for propagating narrow-beam electromagnetic radiation;

FIGS. 2 and 3 are illustrations of typical linear antenna arrays for propagating electromagnetic radiation;

FIGS. 4 and 5 are illustrations of a typical Luneberg lens or geodesic lens for propagating electromagnetic radiation;

FIGS. 6 through 8 are diagrams illustrating the principles of operation of the present invention;

FIG. 9 is a perspective view, in cutaway cross-section, of a portion of an antenna according to the presently preferred embodiment of the present invention;

FIG. 10 is a perspective view of a modification of a wave guide for use in the antenna array illustrated in FIG. 9:

FIG. 11 is an illustration of a typical beam pattern associated with a Luneberg or geodesic lens;

FIG. 12 is a side view elevation, in cutaway cross-section of a Luneberg lens having a lens feed in accordance with the present invention;

FIG. 13 is a section view taken along line 13—13 of FIG. 12 and illustrates a beam pattern associated with a lens in accordance with the present invention;

FIG. 14 is a perspective view of an antenna array utilizing a geodesic lens in accordance with the present invention;

FIG. 15 is a perspective view partly in cutaway cross-section of a missle having an antenna array according to the present invention; and

FIG. 16 is an illustration of the principle of another aspect of the present invention.

ANTENNA ARRAYS

Referring to the drawings, and particularly to FIG. 1, there is illustrated an ordinary parabolic antenna having a reflector 10 and a radiating element 11 for propagating electromagnetic radiation. Radiation propagated by reflector 10 in a narrow beam diagrammatically illustrated between radiation paths 12 and 12'''. Each path 12, 12', 12'', 12''' between element 11 and a plane parallel to the mouth of reflector 10 is equal in length to every other path so that the waves on paths 12–12''' are in phase with each other. Thus, the beam comprises electromagnetic radiation containing planar phase fronts 13, 13', 13'', etc. formed in the beam parallel to the antenna. The parabolic antenna is capable of propagating a relatively narrow "pencil" beam of electromagnetic radiation.

One problem associated with parabolic antennas is that it is often difficult to turn the antenna so as to alter the direction of propagation of the beam. Due to the mechanical considerations involved in turning parabolic antennas, it is often impractical to use parabolic antennas where a relatively fast turning beam is required. Therefore, another type of antenna, known as the "linear or planar antenna array" has been developed to propagate narrow beam electromagnetic radiation. This type of antenna is illustrated in FIGS. 2 and 3.

The linear or planar antenna array illustrated in FIGS. 2 and 3 comprises a plurality of relatively small radiating elements, such as dipole antennas 14, 14', etc arranged in a plane or a line. Generator 15, which is connected to each antenna by means of cable 16, 16', etc., drives the antennas. The antenna array is capable of generating a beam illustrated diagrammatically by radiation paths 17 and 17'''. In the case of a linear array, this beam is a fan beam and is relatively wide in the direction perpendicular to the plane of the drawings, whereas in the case of a planar array the beam is substantially pencil shaped. In either case, generated by the linear or planar array is a narrow beam containing leaner phase fronts 18, 18', etc. By utilizing phase shifting devices 19, 19', etc., in each cable 16, 16', etc., the direction of propagation of the beam may be altered so that the beam is propagated at some angle to the line or plane of antennas 14, 14'. Thus, in FIG. 3 each phase shifting device 19, 19' shifts the phase of the signal delivered to each antenna so that the signal propagated by each antenna is phase-shifted from the adjacent antenna array by a precisely known amount, and angle α is formed between the antenna array and phase fronts 18, 18'. It is to be understood that although the phase-shift devices 19–19''' are shown connected in parallel to the antenna elements, they may also be connected in series so as to achieve the same results.

With the linear or planar antenna array as illustrated in FIGS. 2 and 3, it is possible to propagate a narrow beam of electromagnetic radiation at any desired angle to the line or plane of antenna elements by merely altering the phase relationship between each successive antenna element. Electronic switching means well known in the art can be used to quickly alter the phase relationship as desired. Thus, the linear or planar antenna array offers the advantage over the parabolic antenna of being capable of relatively rapidly changing the direction of propagation of the beam.

One problem associated with the linear or planar antenna array is that it is often difficult to maintain the precise phase relationship for each signal propagated from each antenna element. Ordinarily, the length of the cable between generator **15** and each antenna **14, 14'** must be exactly equal or must contain an accurate phase compensating device so that the signal generated by each antenna element **14, 14'** will be exactly in phase pr phase-shifted by a precisely known amount. Otherwise, the phase fronts of the beam will not be linear or planar and the radiation will not be confined to a narrow beam.

To overcome the problems associated with both the parabolic antenna and the linear or planar antenna array, another type of narrow beam antenna known as the "Luneberg" lens has been developed. In FIGS. **4** and **5** there is illustrated a Luneberg lens **20** for propagating a beam of isotropic electromagnetic radiation having linear phase fronts. The luneberg lens is a substantially circular disc-shaped lens, constructed of a dielectric material having a varying dielectric constant, the maximum dielectric constant being at the center of the lens and decreasing towards the edge. Ordinarily, Luneberg lenses are constructed by means of coaxial rings of different dielectric constants assembled together to form a "stepped" variation in dielectric constant of the lens. The dielectric constant for each ring or "step" of the lens is determined by the following equation:

$$K=2-(r/a)^2 \qquad (1)$$

where K is the dielectric constant of the particular ring section, r is the outer radius of the particular ring section, and a is the radius of the lens. It can be seen from equation (1) that the dielectric constant at the edge of the lens should be equal to 1.0, which is the dielectric constant of free space. The Luneberg lens therefore has a dielectric constant which varies from 1.0 at the edge to 2.0 at the lens center.

The parabolic antenna and linear antenna array both operate on the principle that all of the separate paths for the electromagnetic radiation are of precisely known length, and that therefore all radiation wave fronts arrive into the phase fronts at exactly the same instant and the phase fronts are linear. The Luneberg lens achieves the same results, but instead of using paths of equal length the dielectric constant of each path is different so that signals traveling over the shorter paths are delayed by sufficient lengths of time due to the higher dielectric constant at the center of the lens, and when all radiation arrives at a line in front of the lens, all signals are aligned to form a linear phase front. Hence, referring to FIG. **4**, radiation traveling via paths **21** and **21'** through the lens travels faster than does radiation traveling via paths **21''** or **21'''**. The radiation forms a substantially narrow beam as viewed in the plane of the lens and between lines **22** and **22'** in FIG. **4**. The beam contains linear phase fronts **23, 23'**, etc.

A Luneberg lens is rim-loaded, or fed at the rim, so as to propagate electromagnetic radiation from the lens in a direction parallel to the diameter containing the feed point and normal to the axis. By circularly altering the position of the feed point on the rim, the Luneberg lens is capable of a 360° scan. By utilizing electrical selection means, the scan may be performed substantially instantaneous and needs no cumbersome mechanical scanning apparatus.

There exists another type of radiating antenna, known as the geodesic lens which is similar in principle of operation to both the parabolic antenna and the Luneberg lens. The geodesic lens, unlike the Luneberg lens, has a uniform dielectric constant. However the center of the lens bulges so that all path lengths over the surface between a feed point to a line normal to the direction of propagation in front of the lens are equal. In this manner, signals fed through the lens travel over equal distances to the line of the first linear phase front.

One problem associated with most Luneberg lens and geodesic lens is that the beam propagated by either lens is a fan beam, which is wide in the plane perpendicular to the plane of the lens, as illustrated in FIG. **5**. This is due to the fact that the beamwidth in a given direction is inversely proportional to the length of the antenna in that direction. The beamwidth at the half power points can be determined from the following equation:

$$B.W.=60\,\lambda/L \qquad (2)$$

where B.W. is the beamwidth at the half power points in degrees of an arc, λ is the free space wavelength and L is the length of the antenna array, λ and L being measured in the same units. In the case of a disc-shaped Luneberg lens, the beamwidth in the direction perpendicular to the lens axis and the direction of propagation will be relatively narrow while the beamwidth in the direction of the lens axis will be relatively wide.

The present invention overcomes many of the drawbacks associated with prior art antennas by utilizing an antenna array fed by a lens of the class of Luneberg or geodesic lens. The principle of operation of the present invention is illustrated in FIG. **6**.

LENS-FED ANTENNA

In FIG. **6** there is illustrated a Luneberg lens **25** being fed at a feed point **26**. Although the invention will be described in detail utilizing a Luneberg lens, it is to be understood that a geodesic lens may be substituted therefor. Both the Luneberg lens and the geodesic lens are of the class characterized by having a rim disposed about an axis and defining a substantially circular periphery. Both lenses are further characterized as being capable of being rim fed so as to propagate electromagnetic radiation from the lens in a direction parallel to the diameter containing the feed point and normal to the axis. The radiation pattern through Luneberg lens **25** is shown diagrammatically by paths **27, 27'**, etc. Instead of radiating directly from the surface of the Luneberg lens however, cables **28, 28'**, etc., are connected between the surface of Luneberg lens **25** and antenna elements **29, 29'**, etc. Antenna elements **29, 29'**, etc., instead of being arranged in a straight line as in the case of FIGS. **2** and **3**, are arranged in a circular array having a radius identical to the radius of the Luneberg lens. Thus, the length of each cable **28, 28'**, etc. between Luneberg lens **25** and the antennas **29, 29'** is identical and the phase relationship of the signals radiated by the antennas is such as to form a narrow electromagnetic radiation beam having linear phase fronts **31, 31'**, etc.

FIG. **7** illustrates an extension of the theory illustrated and described in connection with FIG. **6**. Instead of having a plurality of antenna elements mounted some distance from the Luneberg lens, in the array illustrated in FIG. **7**, a plurality of antenna linear arrays of extended length have their bases mounted to the rim of the Luneberg lens. Each linear array is of identical length to every other linear array and the feed structure for each array is analogous in operation to cables **28, 28'**, in FIG. **6**. In FIG. **7** Luneberg lens **32** has an axis **43**, and a plurality of linear arrays **33** of equal lengths are mounted to the periphery of lens **32** in parallel to axis **43**. Since, as shown in equation (2), the beamwidth is inversely proportional to the antenna length in the same direction ($B.W. = 60\,\lambda/L$), the width of the lens **32** determines the width of the beam and the length of arrays **33** determines the height of the beam. Thus, the beam is propagated from the cylindrical array in a narrow pencil-like beam **34** having a width (perpendicular to the lens axis) inversely proportional to the diameter of the lens and having a height (parallel to the lens axis) inversely proportional to the length of the arrays **33**, and containing planar phase fronts **35, 35'**, etc. The lunberg lens operates as a phase correlator or resolver and assures a proper phase relationship between the signals propagated by each linear array **33**. The linear arrays propagate the wave pattern to form the pencil-like electromagnetic radiation beam containing planar phase fronts.

The beam is propagated in a direction perpendicular the the axis of Luneberg lens **32** and diametrically opposite the feed point of the input signal. The shift the direction of propaga-

tion, the input feed point is changed to another position on the rim of the lens by any well-known means to a location diametrically opposite the desired direction of propagation. Thus, it is possible to direct the beam in any direction in a plane normal to the axis of the lens.

If it is desired to alter the direction of propagation of the beam in a plane parallel to the axis of the Luneberg lens so that the direction of propagation is at some angle to the axis other than normal to the axis, delay means is connected to each radiating element 33, 33', etc. to alter the phase relationship between successive radiating elements of each antenna. The operation of this arrangement is illustrated in FIG. 8.

In FIG. 8, there is illustrated Luneberg lens 37 having an axis 43 and a plurality of linear arrays of antenna elements 38, 38', etc. mounted thereto parallel to the axis of the lens and at the periphery or rim thereof. Each array 38, 38' includes phase-shift means 39, 39' adapted to alter the phase of the signal to each element 39*a*, 39*a*'. Thus, if the phase-shift means 39, 39' are spaced along each array 38, 38' in such a manner that each element of the array has its respective signal phase-shifted by an incremental amount, and if each phase-shift increment on a particular array is equal, the beam generated by the arrays 38, 38', etc. will be a narrow pencil-like electromagnetic radiation beam 40 containing planar phase fronts 41, 41', etc., as in the case of FIG. 7. However, in the case of FIG. 8, beam 40 is propagated in a direction from the plane 42 of Luneberg lens 37 by some angle, α. By selecting the location of the input feed point for Luneberg lens 37, the direction of beam 40 in the plane perpendicular to axis 43 of the lens may be selectively altered. By selectively adjusting the phase shift provided by phase-shifters 39, 39', etc., the direction of beam 40 in the plane containing axis 43 may be selectively adjusted.

In FIG. 9 there is illustrated a slotted metal waveguide 50 coupled to Luneberg lens 51 by means of electromagnetic coupler 52. By way of example, coupler 52 may be a short connector, such as the center conductor of a coaxial cable, extending into waveguide 50 and lens 51. Metal radiating waveguides 54, 54', etc., containing dielectric material 56 are coupled to slotted waveguide 50 through slots 55, 55', etc. Slots 55 are formed through one of the narrow walls of waveguide 50. The waveguide may be loaded with a low-loss dielectric material 53. The purpose of the dielectric material is to reduce the wavelength in the waveguide so that slots 55, 55' to the radiating waveguides are spaced approximately one-half wave-length to one full wave-length apart or less. For example, the dielectric constant of the material in the wave-guide approximates 2. The slots may be aligned parallel to each other, or, as shown in the Figure, may be situated at various angles along the length of waveguide 50. By varying the angle of the slots, it is possible to taper the amplitude distribution along the array of waveguides 54 to reduce propagation of side lobes in the vertical plane. Waveguides 54 need not be aligned perpendicular to the axis of wave guide 50, but instead may be inclined at some angle to conserve space. If, however, waveguides 54, 54', etc., are inclined, they should all be inclined at the same angle. By inclining waveguides 54 it is possible to use longer waveguides in a more confined space.

Within each waveguide 54 is a phase shifter comprising a ferrite core 57 aligned with the axis of the waveguide 54 and held in place by holders 57'. Coil 58 is wound around each waveguide 54 and is adapted to be connected to a source of direct current (not shown). By passing a direct current through coil 58, a magnetic field is induced within the associated waveguide 54, the intensity of which is dependent upon the magnitude of the current. The magnetic field alters the permeability of ferrite core 57, and therefore also alters the phase velocity within the particular waveguide 54. By altering the phase velocity of the waveguide, the amount of phase shift of the electromagnetic radiation passing therethrough is likewise altered, thereby altering the phase thereof. By selectively altering the current passing through coil 58, the phase of the electromagnetic radiation propagated by the associated waveguide 54 is correspondingly shifted.

It can be understood from the foregoing that the phase-shifters for each radiating waveguide 54 are fed in parallel from each waveguide 50. The waveguides 50 are distributed in a circular array about the periphery of Luneberg lens and are connected thereto by couplers 52. Hence, radiating waveguides 54 are arranged in a linear array, which in turn is fed by the Luneberg lens. Waveguides 54 are parallel fed through phase-shifters 57, although it is to be understood that a series feed may be used instead of the parallel arrangement.

With the phase-shifted array according to this invention, it is possible to obtain phase-shifts of any desirable magnitude, such as in a directional parallel to the axis of the Luneberg lens (along axis 43 in FIG. 8).

One feature of the arrangement of the phase-shifters along each linear array resides in the fact that a plurality of phase-shifters can be controlled at the same time to change the angle α. Thus, the phase-shifters of each array may be connected to the controller (not shown) so as to receive the same control signal as like phase-shifters of other arrays. Hence, all of the lowermost phase-shifters of each array will shift the phase of the propagated wave by a like amount. Therefore, the number of control signals necessary (at least for a parallel fed arrangement) will be equal to the number of phase-shifters on one array. Any disparity of phase relationship between adjacent arrays is resolved by the lens. In the case of a series-fed arrangement, such as illustrated diagrammatically in FIG. 7, all phase-shifters are operated in a like manner to shift the phase of each successive element by a like amount, from the previous element, so only a single control signal is necessary to operate an all series-fed radiating elements of each linear array. An additional phase-shifter (not shown) may be placed at the entrance to waveguide 50 to reduce cosine error caused by the lens 51.

In FIG. 10 there is illustrated a modification of the invention wherein waveguide 50' is tapered so that the narrow edge faces the center of the Luneberg lens (not shown) and the side portions 59, 59' of waveguide 50' are disposed on separate radii of the lens. The end of waveguide 50' is mounted to the edge or rim portion of the Luneberg lens in the same manner that waveguide 50 in FIG. 9 is mounted to Luneberg lens 51. This arrangement permits more effective reception of the signal propagated through the Luneberg lens and received by the wave guide 50' by permitting a close proximity of mounting of each array and by avoiding spurious radiation.

As illustrated in FIG. 9, Luneberg lens 51 may comprise a dielectric material sandwiched between metal plates 51' and 51'', as hereinafter explained. Also, as will be more fully understood hereinafter, coupler 52 may comprise the driving element of a Yagi antenna which is embedded within the Luneberg lens. The remainder of the Yagi antenna comprises a reflector element 52' and a plurality of directing elements 52''.

LENS FEED

In FIG. 11 there is illustrated a typical radiation pattern for a Luneberg lens. Ordinarily, a radiating Luneberg lens propagates a narrow center beam 60 and several sidelobes 61, 62. Even in the case of an array of antennas fed by means of a Luneberg lens, as described in connection with FIGS. 8–10, the propagated beam will include side-lobes 61 or 62. Ordinarily the side-lobes 61 and 62 represent about 30 percent or more of the total energy of the radiation, and about 70 percent or less energy is radiated in beam 60. It is desirable to diminish the strength of the side-lobes and radiate more energy in the narrow beam. One reason for the side-lobe strength associate with a Luneberg lens is that the Luneberg lens distributes the radiation with a constant amplitude over a relatively wide portion of the circumference of the lens. The radiation pattern of the feed element within an ordinary Luneberg lens is diagrammatically illustrated at 63 in FIG. 11.

One feature of the present invention resides in the provision of a feed arrangement for a Luneberg or geodesic lens which concentrates radiation towards the center of the lens thereby reducing the side-lobes.

To effectuate the concentration of the power towards the center of the LUneberg lens, each feed point is provided with a directional antenna such as a Yagi antenna, embedded within the dielectric material and mounted to a conducting plate. A Yagi antenna is an antenna having a driven element disposed forward of a reflecting element and having a plurality of directing elements forward of the driven element. Thus, as illustrated in FIG. 12, Lunegerg lens 70 has a dielectric material 71 sandwiched between metal plates 72 and 73. Plates 72 and 73 prevent radiation of power from the lens through either the upper or lower surfaces of the lens, and tend to concentrate radiation within the lens.

In accordance with the present invention, several Yagi antennas are disposed about the circumference of the Luneberg lens and connected to one of the conducting plates. Each Yagi antenna comprises driven element 74, reflective element 75 and directing elements 76, 76', etc., embedded in dielectric material 71 and mounted to conducting means 72'. One generating element 74 is connected via lead 77 to the source of power (not shown).

In FIG. 13, the radiation pattern 78 for the Yagi antenna illustrated in FIG. 12 is shown as concentrating radiation toward the center of the opposite edge of the lens. By comparing pattern 78 in FIG. 13 with pattern 63 in FIG. 11, it can be seen that most of the energy is directed toward the center of the Luneberg lens 71 so as to be concentrated diametrically opposite the Yagi antenna. The propagated beam 79 contains more energy than heretofore obtained, and less energy is permitted to be transmitted in the side-lobes 80, 80'. With the use of the Yagi directional antenna as a feed element for a Luneberg or a geodesic lens it is possible to obtain as much as, or even greater than 95 percent of the energy in beam 79, thereby allowing less than 5 percent of the radiation to appear in side-lobes.

FIG. 14 illustrates a geodesic lens 85 having a rim defining a generally circular periphery. Unlike the Luneberg lens, the dielectric constant of the material forming the geodesic lens does not vary throughout the lens, but instead is uniform throughout the lens. The geodesic lens includes a geodesic bulge 86. Electromagnetic radiation propagated from any point on the rim of the geodesic lens travel along a plurality of paths, each closely following the surface 86 of the lens to points on the rim from where the radiation emerges to form a narrow beam wave. This radiation will propagate as electromagnetic radiation having linear phase fronts. The parallel relationship of the linear phase fronts of the electromagnetic radiation is achieved by virtue of the fact that all paths for electromagnetic radiation within the geodesic lens are of equal length from the feed point to a line in the beam perpendicular to the direction of propagation. Thus the path length of electromagnetic radiation traveling diametrically across the lens and over the bulge, is equal to the path length of electromagnetic radiation traveling across a chord of the lens and continued to the line of equal phase.

As illustrated in FIG. 14, a plurality of waveguides 50'' are mounted to one surface of the geodesic lens. Waveguides 50'' may be provided with suitable radiating elements as described in connection with FIGS. 9 and 10.

FIG. 15 illustrates a practical application of an antenna array and feed mechanism in accordance with the present invention. In FIG. 15 there is illustrated a missile 100 having a skin 101. Luneberg lens 102 is axially mounted in the missile so that its axis is concentric with axis 103 of the missile. A plurality of waveguides 50, 50', etc., is connected to lens 102 in the manner described in relation to FIG. 9 to form an array of antennas as hereinbefore described. Waveguides 54, 54' are mounted to each of waveguides 50, 50' in the manner hereinbefore described. Control mechanism 104 is connected to Luneberg lens 102.

Assuming that the missile is providing communication to ground or other facilities and that the missile is to direct information via a directional beam of electromagnetic radiation, controller 104 operates to feed a signal to a particular location on the rim of the Luneberg lens 102 and operates on the phase shift coils 58 (FIG. 9) of each of the radiating elements to cause a narrow beam of electromagnetic radiation carrying the desired information to be propagated in the desired direction as heretofore described. The radiating waveguides 54, 54' etc., may be situated so that the radiating ends of the wave guides form part of the skin of the missile.

If it is desired to control the missile illustrated in FIG. 15, such control is possible by means of an array of receiving antennas and a Luneberg or geodesic lens. The arrangement may be the same as hereinbefore described in FIGS. 9–15, except that instead of being radiating antennas, antennas 54, 54' are receiving antennas adapted to receive electromagnetic radiation from a remote source. Such radiation propagated by the remote source would arrive as planar phase fronts. Such radiation beams could, for example, be propagated by means of an antenna array in accordance with the present invention and described in connection with FIGS. 9–14.

Referring to FIG. 16, the incoming beam 110 is a beam of electromagnetic radiation and contains a plurality of planar phase fronts 111, 111', etc. The radiation is received by the array of antennas which in turn induce signals into Luneberg lens 112 from a plurality of points 113, 113', etc. From each point 113, 113', etc., radiation is directed throughout the entire Luneberg lens. However, there is only one point where all the signals will be in phase, and that point is output point 114, which is on the opposite side of the Luneberg lens and aligned with the incoming beam 110.

Circuitry may be associated with the rim of the Luneberg lens in such a manner as to determine the point on the rim where all the signals are in phase. That point lies on the diameter of the lens parallel to the direction of the beam received by the antennas. Control circuitry such as controller 104 in FIG. 15 may be utilized in such a manner as to operate a missile upon command of a remote station received from a particular direction.

One feature of the antenna system described herein resides in the fact that the antenna element 54 (FIG. 9) can transmit or receive electromagnetic radiation. Hence, in FIG. 9, coupler 52 may constitute the driven element of a Yagi antenna as described in connection with FIGS. 12 and 13, and reflector element 52' and directing elements 52'' may be mounted to plate 51'' of lens 51 for directing radiation through the lens. Coupler 52 thereby has the dual function of being the driven element of a directional antenna in case the element is a selected feed point for the lens, or it may act as a coupler for directing radiation received by it between the lens and waveguide 50. In either case, one Yagi antenna couples the lens to a transmitter or receiver and the other Yagi antennas couple the lens to individual arrays.

As shown particularly in FIG. 13, a transmitter or receiver 120 may be connected to element 74 of each Yadi antenna within the lens. In the transmitting mode, selection means (not shown) within the transmitter may direct the signal to be transmitted to a selected one of elements 74 for propagation across the lens and into waveguides 50 (FIG. 9) for propagation into space as heretofore explained. In the receiving mode the receiver receives signals from all elements 74 as propagated through the lens and determines which element 74 receives signals entirely in phase, as heretofore explained. For example, the receiver may include a suitable level sensing circuit (not shown) or other circuitry for determining which element receives signals in phase. As heretofore explained, the element 74 which receives the signals in phase is aligned with the incoming beam.

The present invention thus provides an antenna array for propagating a narrow electromagnetic radiation beam. The apparatus is efficient in use, and may be utilized to rapidly scan in any desired direction. Thus, the antenna array may be utilized for scanning throughout an entire spherical area. The lens, whether it be a Luneberg lens or a geodesic lens, provides unique operation as a phase resolver for the antenna array.

The antenna system according to the present invention is particularly useful as a directional receiving antenna for a missile for receiving radiation from a target and operating on control circuitry on the missile for directing the missile at the target. The signals received by the missile could be generated by the target, for example, the target's communication system, radar, or jammer, or could be reflected from the target, for example as echoes from the missile's radar. In this latter case, the radar signal transmitted by the missile could be propagated by the antenna to reflect from the target and received by the missile by the same antenna to operate suitable control circuitry. In this respect, the missile could track elusive targets.

This invention is not to be limited by the embodiments shown in the drawing or described in the description, which are given by way of example and not of limitation, but only in accordance with the scope of the appended claims.

What is claimed is:

1. An antenna array for propagating electromagnetic radiation comprising: a lens of the class characterized by having a rim disposed about an axis and defining a substantially circular periphery, the lens being further characterized by being capable of being rim fed so as to propagate fan-beam, electromagnetic radiation containing linear phase fronts from the lens diametrically opposite the feed point in a direction parallel to the diameter containing the feed point and normal to said axis; a plurality of connection means each having an end mounted to said lens adjacent said rim, said plurality of connection means being mounted in circular array for receiving electromagnetic radiation from said lens; a plurality of first waveguides mounted to respective ones of said connection means; a plurality of second waveguides each having an end mounted to a respective first waveguide for propagating electromagnetic radiation received by the respective first waveguide from said connection means; and feed means for coupling electromagnetic radiation to said lens adjacent said rim.

2. Apparatus according to claim 1 wherein said lens is selected from the group consisting of Luneberg lenses and geodesic lenses.

3. Apparatus according to claim 1 wherein said feed means comprises a plurality of feed inputs mounted to said lens adjacent the periphery thereof and adjacent said rim, said feed inputs being adapted to be individually connected to a signal source.

4. Apparatus according to claim 3 wherein said feed means includes a directional antenna for propagating electromagnetic radiation substantially diametrically across said lens.

5. Apparatus according to claim 4 wherein said directional antenna is a Yagi antenna.

6. Apparatus according to claim 1 further including phase-shift means for simultaneously varying the degree of phase-shift between each radiating waveguide on a respective first waveguide by an incremental amount.

7. Apparatus according to claim 6 wherein said phase shift means comprises a ferrite core disposed in each of said second waveguides and a coil disposed about each of said cores, whereby when a direct current of a preselected magnitude is passed through selected coils, the phase velocity of the respective second waveguide is altered, thereby altering the phase of the electromagnetic radiation propagated by the selected second waveguide.

8. Apparatus according to claim 1 wherein said first and second waveguides are filled with a dielectric material.

9. Apparatus according to claim 1 further including phase-shift means for simultaneously varying the degree of phase-shift between each radiating antenna on a respective array by an incremental amount.

10. An antenna array for receiving electromagnetic radiation from a remote source and for determining the direction from which such radiation is received, said array comprising: a lens of the class characterized by having a rim disposed about an axis and defining a substantially circular periphery, the lens being further characterized by being capable of being rim fed so as to propagate fan-beam, electromagnetic radiation containing linear phase fronts from said lens diametrically opposite the feed point in a direction parallel to the diameter containing the feed point and normal to said axis; a plurality of connection means each having an end mounted to said lens adjacent said rim, said plurality of connection means being mounted in a circular array for propagating electromagnetic radiation into said lens; a plurality of linear antenna arrays wherein each of said antenna arrays comprises a first waveguide mounted to said lens and a plurality of second radiating waveguides having an end mounted to a respective first waveguide each of said arrays being mounted to a respective one of said connection means for receiving electromagnetic radiation from said remote source and for propagating the radiation into the respective connection means; and a plurality of output means connected to the rim of said lens and each adapted to be connected to a electrical load device, said output means delivering an electric signal to said load device upon receipt of co-phasal electromagnetic radiation from said plurality of connecting means.

11. Apparatus according to claim 10 wherein said lens is selected from the group consisting of Luneberg lenses and geodesic lenses.

12. Apparatus according to claim 10 wherein said first and second waveguides are filled with a dielectric material.

13. Apparatus according to claim 10 wherein said connecting means includes coupling means coupling the output from each of said first waveguides into said lens, each of said coupling means including a directional antenna mounted in said lens adjacent the end of a respective first waveguide, each of said directional antennas being adapted to propagate electromagnetic radiation substantially diametrically across said lens.

14. Apparatus according to claim 13 wherein each of said directional antennas is a Yagi antenna.

15. An antenna array for propagating electromagnetic radiation comprising: a lens of the class characterized by having a rim disposed about an axis and defining a substantially circular periphery, the lens being further characterized by being capable of being rim fed so as to propagate fan-beam, electromagnetic radiation containing linear phase fronts from the lens diametrically opposite the feed point in a direction parallel to the diameter containing the feed point and normal to said axis; a plurality of connection means each having an end mounted to said lens adjacent said rim, said plurality of connection means being mounted in a circular array for receiving electromagnetic radiation from said lens; a plurality of linear antenna arrays mounted to respective ones of said connection means for propagating the electromagnetic radiation received from said connection means, each of said arrays including a plurality of radiating antenna means; and feed means for coupling electromagnetic radiation to said lens adjacent said rim, said feed means comprising a plurality of feed inputs mounted to said lens adjacent the periphery thereof and adjacent said rim, said feed inputs being adapted to be individually connected to a signal source, and a plurality of Yagi antennas individually connected to said feed inputs for propagating electromagnetic radiation substantially diametrically across said lens.

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