

July 9, 1968

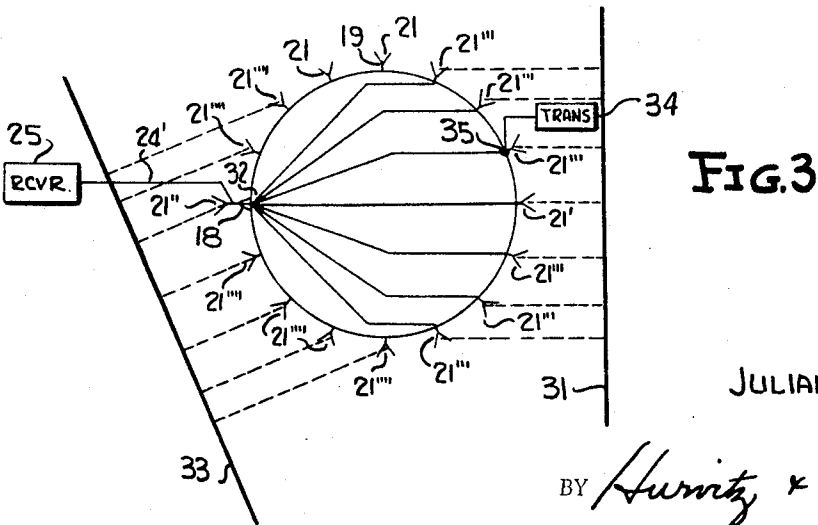
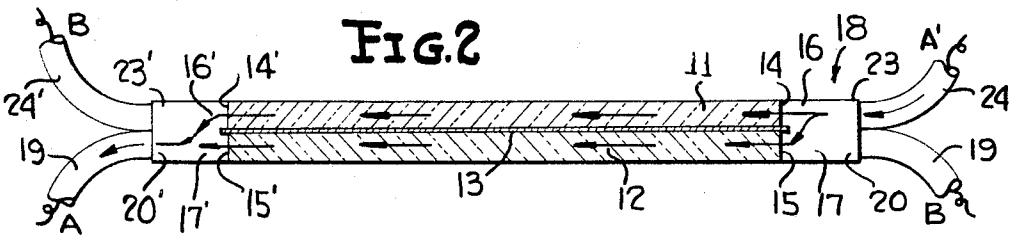
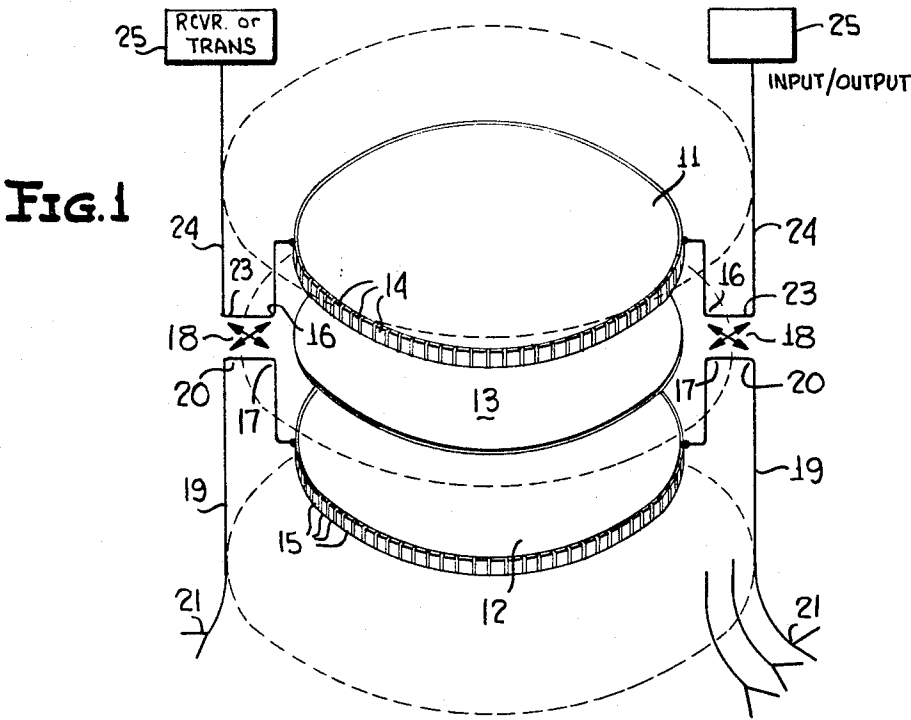
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STEERABLE LUNEBERG ANTENNA ARRAY

Filed April 15, 1964

2 Sheets-Sheet 1



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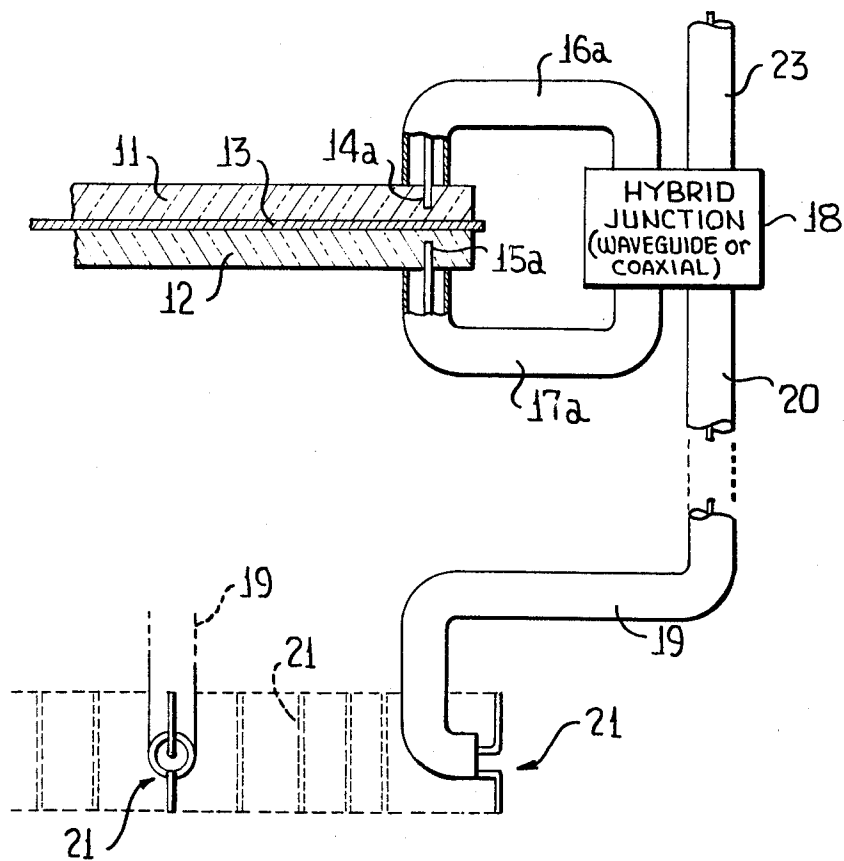
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FIG. 4



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**STEERABLE LUNEBERG ANTENNA ARRAY**  
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### ABSTRACT OF THE DISCLOSURE

A steerable antenna array includes a pair of juxtaposed parallel Luneberg lenses of circular planar configuration, with electromagnetic energy feeds disposed at equal intervals about the periphery of each lens. The aligned pairs of feeds for both lenses are coupled to separate respective arms of a hybrid junction, the other arms of which lead to transmitter, receiver, or appropriate termination, and to radiating elements of the array. Thus, the number of hybrid junctions and radiating elements is equal to the number of feeds for each lens. The hybrid junctions introduce phase shifts in the energy extracted from incoming electromagnetic waves or in the energy to be applied to the radiators, which are arranged in a planar circular array of the same electrical diameter as the lenses and connected by equal length lines thereto, and the lenses produce convergence or divergence of the energy therethrough depending on whether reception or transmission is currently being practiced, to insure that energy is transferred only between radiators and an electromagnetic energy transducer, whether transmitter or receiver, rather than in whole or in part between the radiators themselves or between several transducers.

The present invention relates generally to steerable antenna arrays and more particularly to an array wherein plural, individual radiators are coupled to a focus point by an electromagnetic lens.

Previous approaches to steerable antenna arrays have generally fallen into two classes. The first class involves mechanically moving the beam by a servo mechanism, a large reflector or a lens, to a location where it is pointed in the desired direction. Of course, this is undesirable because movement of a large mass is cumbersome, time consuming and inefficient. In addition, the aperture of such an arrangement can point in only one direction so that energy can be coupled to or feed from the antenna in only one direction at a time.

To avoid these problems, electronically steerable antenna arrays were developed. In an electronic steering system, a multiplicity of radiators is provided. According to one approach, the radiators are coupled to a network including phase shifters and attenuators which are varied to control the direction of the major axis of the resulting array pattern. In other systems, variable phase shift is attained by changing the frequency of the energy coupled between the phase shifters and the antenna array. Steerable antenna arrays of these types inherently are narrow bandwidth devices because phase shifters are basically frequency dependent. Whenever it is desired to steer wide bandwidth patterns through large angles relative to their normal axis, the phase shifters do not introduce the proper phase shift and materially attenuate the power fed through them. In consequence, large boresight errors and pattern degradation result. A further disadvantage attendant with the frequency changing or scanning systems is that the beam is properly steered at only the center frequency. If wideband information is coupled to such a system, its propagation direction is not fixed but is a function of frequency.

A specific approach to the problem of wideband, electronic steerable arrays is the utilization of multiple fixed

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phase shifters that are selectively connected to one of a plurality of separate positions commensurate with the direction at which the antenna is adapted to be steered. While this system operates satisfactorily over a wide frequency range, it requires many precisely fabricated components, hence is expensive and complicated.

In accordance with the present invention, a simple, wide bandwidth electronically steerable antenna is provided by coupling a plurality of discrete radiators through a lens system to a focus point. In a preferred embodiment of the invention, the lens system comprises a pair of isolated Luneberg lenses wherein waves propagating through a point at one of its peripheral edges are refracted and converted into plane waves emerging from or coupled to the other peripheral lens edge. To enable energy to be transmitted or received in any direction, an antenna is connected at each individual location about the periphery of the lens system. At a focus point opposite the peripheral edge at which plane wave energy emerges from or impinges on the lens system and along a lens diameter at right angles to the plane wave, an external device, i.e. a transmitter or receiver, is connected. Energy is coupled only between the lens system and the external device only at the focus point.

To couple energy simultaneously between the lens and several external devices in different directions, a coupling network, such as a hybrid, is connected at each peripheral point on the lens system. The coupling networks introduce phase shifts so that energy is transferred via the lens system only between the external devices and the radiators, not between the several radiators or between plural external devices.

It is, accordingly, an object of the present invention to provide a new and improved wide bandwidth, electronically steerable antenna array.

A further object of the invention is to provide a new and improved electronically steerable antenna array wherein plural waves can be transmitted and/or received at a time.

An additional object of the invention is to provide a wide bandwidth steerable antenna array wherein a lens couples wide band energy between a point and a plane surface without the need for adjustable phase shifters or attenuators.

Still another object of the invention is to provide a new and improved lens system especially adapted for utilization with steerable antenna arrays.

Yet an additional object of the invention is to provide a new and improved steerable antenna array wherein energy can be propagated in any direction.

Still a further object of the invention is to provide a new and improved steerable antenna array employing a system that is relatively inexpensive, not complicated and yet provides a uniform response over a wide bandwidth.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of one specific embodiment thereof, especially when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 is a perspective, exploded view of a preferred embodiment of the invention;

FIGURE 2 is a side sectional view taken through a diameter of the lens of FIGURE 1;

FIGURE 3 is a top view of the lens of FIGURE 1; and

FIGURE 4 is a side fragmentary sectional view of the lens structure, illustrating the coupling or transitional arrangement between coaxial lines and lenses, and between feed lines and dipole antenna elements, and further showing the coupling of antenna array, transducers, and lenses via hybrid junctions.

Referring now to the drawing in general, and to specific figures where clarity dictates, Luneberg lenses **11** and **12** are provided in the form of discs or plates disposed in parallel planes, and are separated by a metal shield **13** to prevent energy coupling between the lenses. Each of lenses **11** and **12** has an index of refraction  $n$ , that varies as a function of radial position,  $r$ , in accordance with

$$n = \sqrt{D + r^2}$$

where  $D$  is the diameter of each disc. In accordance with well known principles, such lenses have the property that an electromagnetic plane wave introduced into the periphery of the lens is focused to a point on or near the surface at the diametrically opposite side. Lenses **11** and **12** are merely conventional circularly (essentially two-dimensional) symmetric Luneberg lenses, a simpler version than the three-dimensional spherically symmetric type. As is well known, the variable index of refraction is obtained by employing successive rings of differing dielectric constants.

Spaced about the perimeter of lenses **11** and **12** are discrete, insulated metal electrodes **14**, **15**, for introducing RF energy into the respective lenses upon appropriate excitation via lines **16** and **17**. In practice, the electrodes may comprise probe transition units such as those shown in FIGURE 4, in which the center conductors **14a**, **15a**, of coaxial transmission lines **16a**, **17a**, respectively, are partly imbedded in the lenses. Pairs of electrodes or probes **14**, **15** on the separate lenses are aligned, the electrodes of each pair being connected to colinear arms **16**, **17** of separate short slot three db hybrid couplers **18**. While FIGURE 4 is a fragmentary side sectional view of the lens structure showing only one pair of aligned probes, it will be understood that corresponding probes are equally spaced about the periphery of the lenses in the same manner as illustrated in that figure, and are excited via arms of other hybrid junctions **18**. Coupled via equal length vertically extending transmission lines **19** from another arm **20** of each hybrid **18** are respective dipole antennas **21**, one of which is shown connected to its coaxial feed line in FIGURE 4, with others shown in a phantom schematic view of the array. As shown more clearly in FIGURES 1 and 3, antenna elements **21** are arranged in a circular array so that plane parallel electromagnetic waves can be transmitted toward or received from any direction. The other arm **23**, colinear with arm **20**, of each coupler **18** is connected via transmission line **24** to an external transducing device **25**, such as a transmitter, a receiver, or an impedance matching termination, the latter being employed if neither of the former is. The criterion for the type of device **25** utilized is determined by the desired direction of propagation or reception.

As shown in FIGURE 4, each of center conductors **14a**, **15a**, acting as a probe transition, extends into its respective lens **11**, **12** to a point short of metal shield **13**. For the sake of clarity, only two hybrid combiners are shown in FIGURES 1 and 2, but it is to be understood that one combiner is provided for each pair of aligned probes **14**, **15** about the periphery of Luneberg lenses **11**, **12**, as indicated by the circular dotted line (FIGURE 1) through the combiners in accordance with normal drafting convention. Similar circular dotted lines in FIGURE 1 in the regions of transmission lines **19** and **24** serve a corresponding purpose, viz., to indicate that a circular array of antenna elements **21** (FIGURE 3) and respective feed lines are present, and that there exists a symmetrical arrangement or appropriate positional change for transducers **25** and coupling lines **24** according to desired direction of transmission and/or reception of electromagnetic waves at the antenna array. The number and spacing of aligned pairs of probe transitions **14**, **15** about the periphery of lenses **11**, **12** depends upon desired beam steering resolution.

Each of antennas **21** is positioned at a point approxi-

mately below its corresponding electrode **15** so that the electrical diameter of the antenna array is substantially equal to that of lenses **11** and **12**. If the array and lens electrical diameters are not substantially equal, the effect of the principal characteristic of the Luneberg lens, i.e., focusing a plane wave to a point, is partially lost. That is to say, portions of the electromagnetic wavefront arriving at each antenna (assuming reception, for the moment) must be coupled into the lenses with precisely the same relative phase displacements, to ensure that a composite plane wave having characteristics corresponding to those of the arriving wave is introduced into each lens **11**, **12** at the appropriate probe transition points, for focusing to a point at the diametrically opposite side. Minor deviations in the two diameters cause the beam to tilt over a small arc, producing pattern deviations preventing the focusing of the plane wave.

In operation of the system for reception of incoming RF waves, a plane wave having wavefront **31** (FIGURE 3) arrives at the steerable array from a direction normal to the diametric line through antenna elements **21'** and **21''**. The hybrid junction **18** associated with the pair of aligned electrodes at focal point **32** is coupled via its arm **23** and transmission line **24'** to the input of a receiver **25**. Arms **23** of the remaining hybrids are connected to separate matched terminating impedances to prevent the return of signal reflections to these hybrids through their respective lines **24**.

Energy from incoming wave **31** absorbed by each of antennas **21'** and **21''** (FIGURE 3) is coupled by coaxial feed lines **19** of equal electrical length to the arms **20** of respective hybrid junctions **18** (FIGURES 1, 2, 4). Accordingly, the relative phase relationships of the wave portions received at the antennas are maintained for the RF energy fed into arms **20** of the respective hybrids. This energy is supplied in parallel to Luneberg lenses **11** and **12** via colinear hybrid arms **16** and **17** and coaxial probe transition units **14a**, **15a**, respectively, the energy coupled to lens **11** being phase shifted by  $90^\circ$  relative to that deriving from lines **19** and applied to lens **12** by virtue of the characteristic function of the hybrid junctions **18**.

The plane waves in phase quadrature are launched in lenses **11** and **12** by excitation of the lenses with the RF energy emanating from the hybrid junctions through the respective coaxial lines **16a**, **17a**, and probe transition units **14a**, **15a**, respectively (FIGURE 4). The wave energy is substantially confined to the dielectric lenses by virtue of the impedance discontinuities occurring at the boundary of the lenses and the surrounding medium. Losses occurring as a result of the escape of some of the RF energy to the surrounding medium are relatively slight. It will be observed that the probe transition units are located at or near the periphery of the respective lens, and that in the event of "backward" wave energy, i.e., RF energy that travels in the lens in a direction opposite that leading to the point at which the plane wave is focused, reflections will occur at the edge boundary of the lens (owing to the impedance discontinuity thereat) to produce a standing wave in the direction of focusing, similar to the phenomenon occurring in a waveguide. The wave energy focused to point **32** (FIGURE 3) by the action of lenses **11**, **12**, is absorbed by the pair of aligned probe transition units appearing at that point, for application to the associated hybrid via arms **16** and **17**.

Because lenses **11** and **12** have identical dielectric, and hence, phase velocity characteristics, there is no relative phase shift in the energy propagated between associated electrode pairs. Thus, half the energy intercepted by antenna **21'** arrives at focus point **32** via lens **11** and half via lens **12**, the energy propagated through the latter arriving at point **32** exactly  $90^\circ$  out of phase relative to the energy transmitted via the former.

At focal point **32**, the energy fed through the two lenses is recombined by the hybrid **18** that is connected

to electrodes 14' and 15'. The energy fed by colinear arms 16' and 17' undergoes a further 90° phase shift as it is supplied to the other colinear arms 23' and 20', respectively. This results in cancellation of the energy supplied to arm 20', and addition of the energy coupled to arm 23' because arms 16' and 17' are excited by waves displaced by 90°. In consequence, no energy is coupled to antenna element 21'' and all of the energy focused on point 32 is fed to receiver 25 via line 24'. Plane waves directed towards lenses 11 and 12 at directions other than the propagation direction of wave 31 are focused at points other than point 32 and are not coupled to receiver 25.

Because hybrids 18 are 90° phase shifters over a very wide frequency range and there is no relative phase shift of energy propagating through lenses 11 and 12, the system has very wideband capabilities.

The resolution angle of the lens system is determined by the length of electrodes 14 and 15 about the perimeter of lenses 11 and 12. If the system is designed to receive waves over a relatively large angle, i.e. a low resolution system, electrodes 14 and 15 are long and need not be numerous. But, a system of high resolution requires many electrodes of short length about the perimeters of the lenses.

When it is desired to steer the antenna pattern so it is responsive to plane waves propagated in directions other than the propagation direction of wave 31, it is merely necessary to connect receiver 25 to the hybrid at which the plane waves of interest are focused. The focus point is the electrode on the periphery of lens 11 lying on a radial at right angles to the received plane wave and on the edge of the lens opposite from the edge that first intercepts the received energy.

A feature of the invention is that the same apparatus may be utilized for simultaneously transmitting or receiving more than one wave length in different directions. Thus, if plane wave 31 of frequency  $f_1$  is focused on point 32 so receiver 25 is responsive to it, plane wave 33 of frequency  $f_2$  is simultaneously propagated from antennas 21'' and 21''' by connecting transmitter 34 to arm 23 of the hybrid at focus point 35. In a similar manner, the impedance termination at each of the other hybrid arms 23 may be substituted for a transmitter or receiver, depending upon the desired direction of transmission and/or reception.

It is to be understood that lenses other than Luneberg lenses may be employed if they have the ability to focus a plane wave into a point and there is no relative phase displacement in propagating two waves through the individual lenses. Exemplary of such a lens is the Geodesic lens, which, however, is more difficult to manufacture than the Luneberg lens.

While I have described and illustrated one specific embodiment of my invention, it will be clear that variations of the details of construction which are specifically illustrated and described may be resorted to without departing from the true spirit and scope of the invention as defined in the appended claims.

I claim:

1. A steerable antenna system for coupling energy between at least one external device and an antenna array wherein said device comprises a transmitter or receiver, comprising a pair of round planar dielectric lenses, each of said lenses having an index of refraction varying as a function of radius so that parallel beams of electromagnetic energy at one edge thereof are focused at a predetermined point on the opposite edge thereof, means for coupling energy between each antenna of said array and a respective one of a plurality of aligned discrete points on the edge of both of said lenses and for coupling energy between each of said external devices and a separate one of said plural aligned discrete points on the edges of both of said lens.

2. In combination, a pair of flat circular lenses dis-

posed in spaced parallel planes, each of said lenses having an index of refraction varying as a function of radius to focus electromagnetic energy incident on one edge thereof at a predetermined point on the opposite edge thereof, a plurality of hybrid couplers, adjacent colinear arms of each of said couplers being coupled to aligned points on the edges of both of said lenses for translation of electromagnetic energy to and from said lenses, and a planar circular array of antenna elements each connected to a respective one of said couplers, said array having an electrical diameter substantially equal to that of each of said lenses.

3. In combination, an antenna array comprising a plurality of discrete radiating elements, an external electromagnetic wave transducing device, and means for coupling energy between a point coupled to said device and plural points individually coupled to said elements; said means including a pair of spaced parallel planar Luneberg lenses, and hybrid coupler means coupling said point to said device and said plural points to said elements to combine electromagnetic energy for translation between said device and said elements only.

4. In combination, a pair of flat circular lenses shielded from each other, each of said lenses having an index of refraction varying as a function of radial position so that electromagnetic waves appearing at one point on the periphery thereof appear as plane waves along the periphery at the diametrically opposite side, a transmitting or receiving device, and means for coupling energy between a pair of aligned points at each of equal intervals around the periphery of said lenses and said transmitting or receiving device, one of said coupling means being provided for each pair of aligned points on the periphery of said lenses.

5. The combination of claim 4 wherein each of said lenses is a Luneberg lens.

6. The combination of claim 4 wherein each of said coupling means comprises a hybrid combiner.

7. In combination, a pair of parallel aligned dielectric disc lenses each having a radially varying index of refraction, a circular array of radiators equally spaced about the periphery of said lenses, and means for coupling energy between individual equally spaced, aligned points about the periphery of said lenses and each of said radiators, said points aligned in pairs on said pair of lenses, one of said coupling means being provided for each pair of said points and a respective radiator.

8. The combination of claim 7 wherein the electrical diameter of said lenses is equal to the electrical diameter of said array.

9. The combination of claim 7 wherein each of said means for coupling shifts the phase of the energy coupled between one of said radiators and a point on one of said lenses 90° relative to the phase of the energy coupled between the respective radiator and the aligned point on the other radiator.

10. A steerable antenna comprising at least one electromagnetic energy transducer, an array of electromagnetic energy radiating elements, dielectric lens means for focusing electromagnetic energy incident along one side thereof to a point on the opposite side thereof without substantial phase displacement along individual paths therebetween, and means for coupling energy between said at least one transducer and said lens means and between said radiating elements and said lens means to permit substantial energy transfer between said array and said transducer only, said coupling means including a plurality of substantially equally spaced electromagnetic feeds disposed in aligned pairs about the surface of said lens means.

11. The antenna according to claim 10 wherein said radiating elements are arranged in a planar circular array and equally electrically separated from said lens means by said energy coupling means.

12. The antenna according to claim 11 wherein said

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lens means comprises a pair of planar spaced parallel Luneberg lenses, each having an electrical diameter corresponding substantially to that of said circular array, one feed of each of said aligned pairs located at the periphery of each lens directly opposite a correspondingly disposed feed on the other lens. 5

13. The antenna according to claim 12 wherein said energy coupling means comprising means for introducing a quadrature phase displacement between energy transferred to said lenses and for combining energy emerging from said lenses to cancel substantially all energy transfer except that between said transducer and said radiating elements. 10

14. The antenna according to claim 12 wherein said

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energy coupling means comprises a separate hybrid coupler for each of said radiating elements, and equal length transmission lines between each coupler and its respectively associated radiating element.

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