

- [54] **CIRCULARLY SYMMETRIC
RETRODIRECTIVE ANTENNA**
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- [73] Assignee: **The United States of America as
represented by the Secretary of the
Navy**, Washington, D.C.
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- [51] Int. Cl. **H01Q 3/26**
- [58] Field of Search **343/753, 754, 854, 100 TD,
343/816**

3,340,530 9/1967 Sullivan et al. 343/DIG. 2

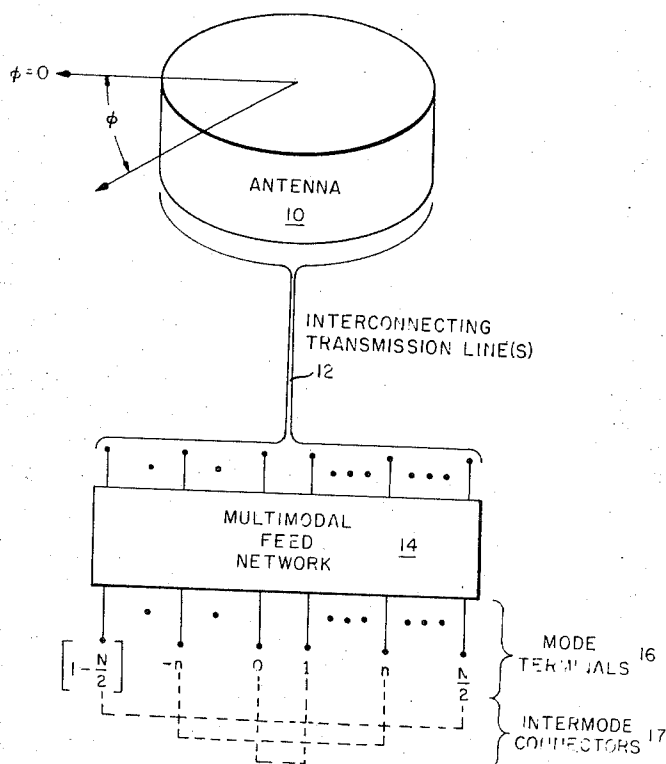
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[57] **ABSTRACT**

A method and apparatus for obtaining automatic retrodirective performance from circularly symmetric arrays, and circular continuous aperture antennas. Phased mode sets are provided by a multimodal feed network as a result of modal interconnection methods. All modes in a particular mode set become in phase in the direction of an incoming signal, and as a result, a beam is made to reradiate in that direction. The method is applicable to two and three-dimensional retrodirective systems and includes both active and passive devices. Also, the reradiated beam width, beam power, and other reradiated beam characteristics including sidelobe functions, are capable of being controlled and adjusted.

15 Claims, 4 Drawing Figures

- [56] **References Cited**
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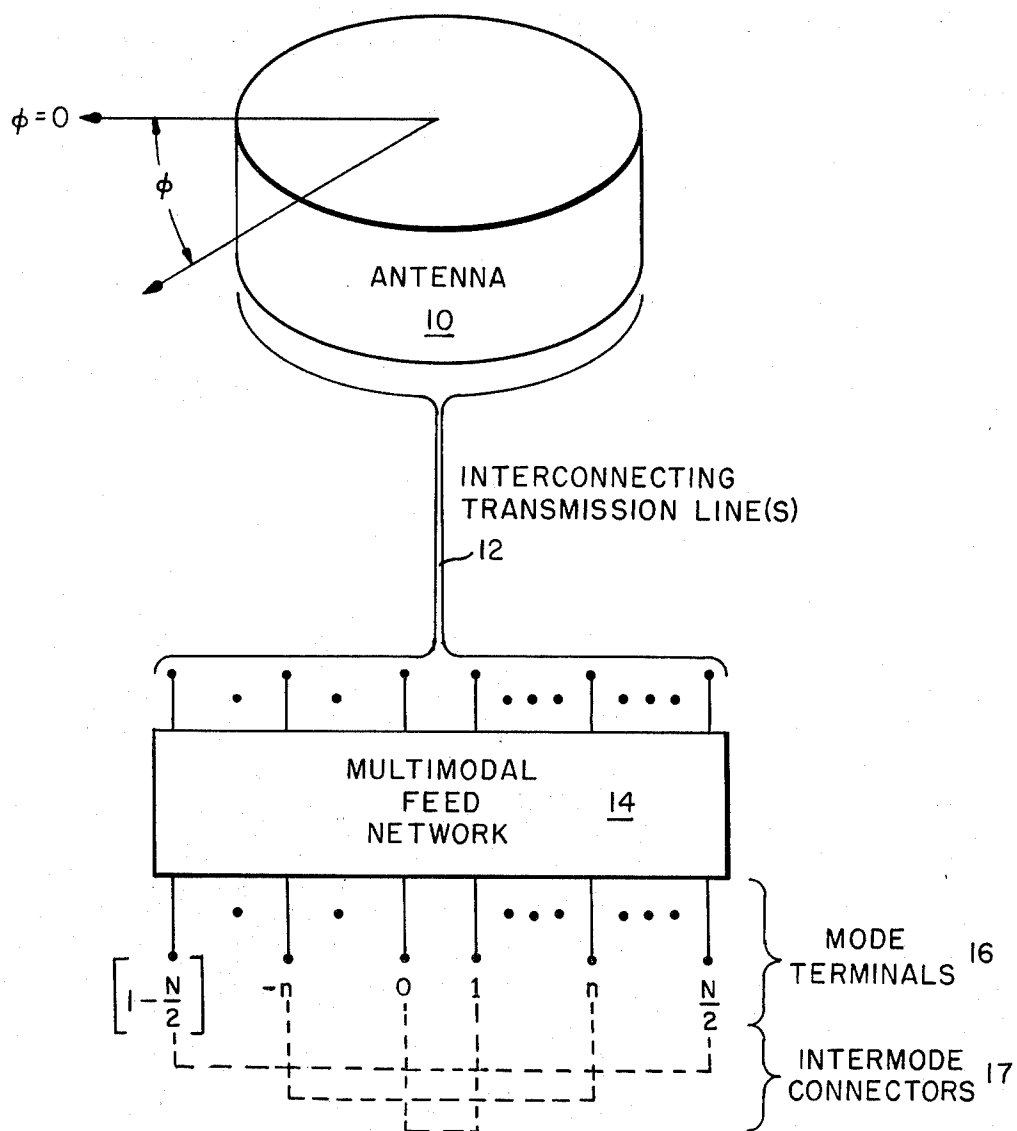


FIG. 1.

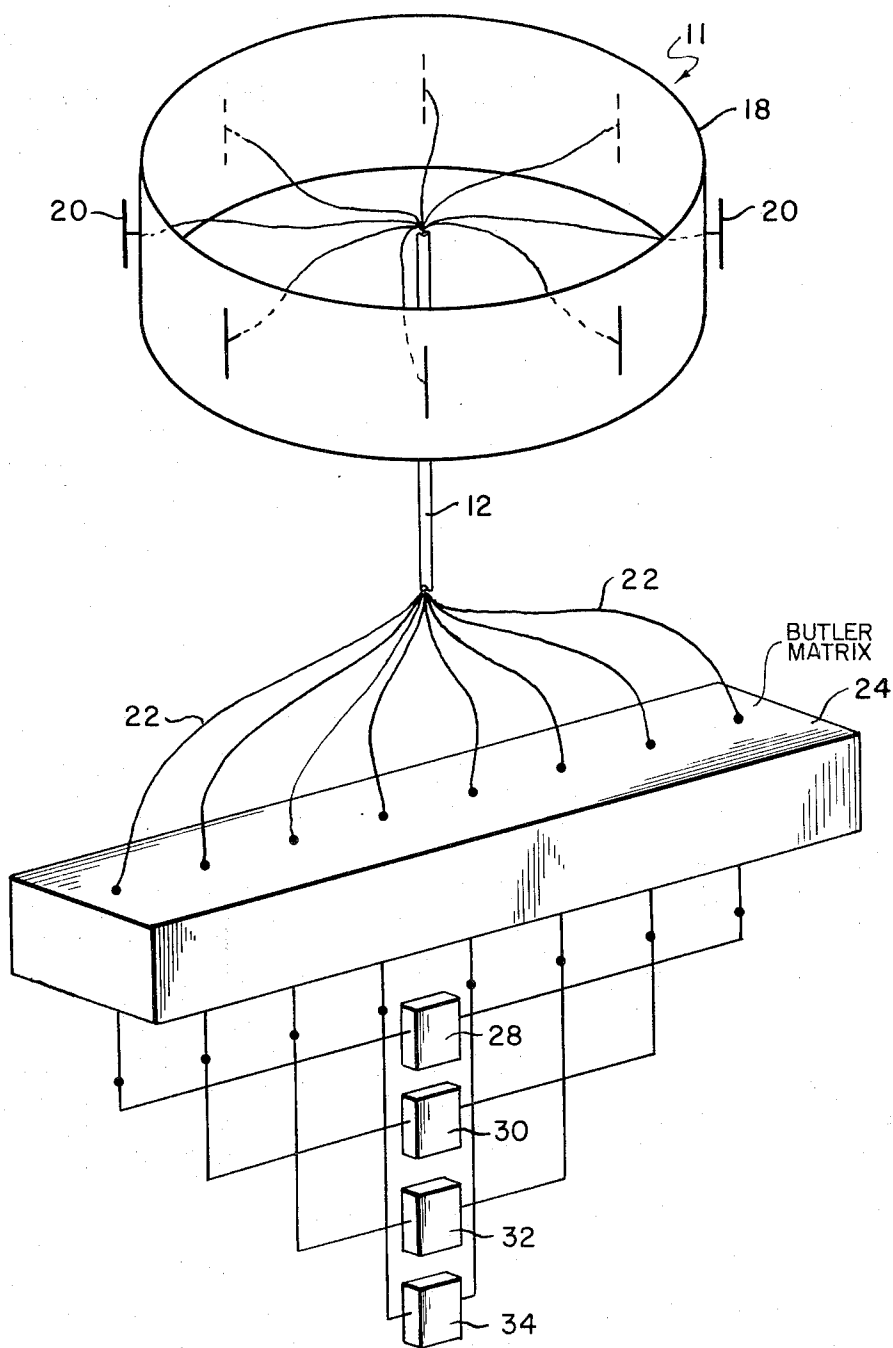


FIG. 2.

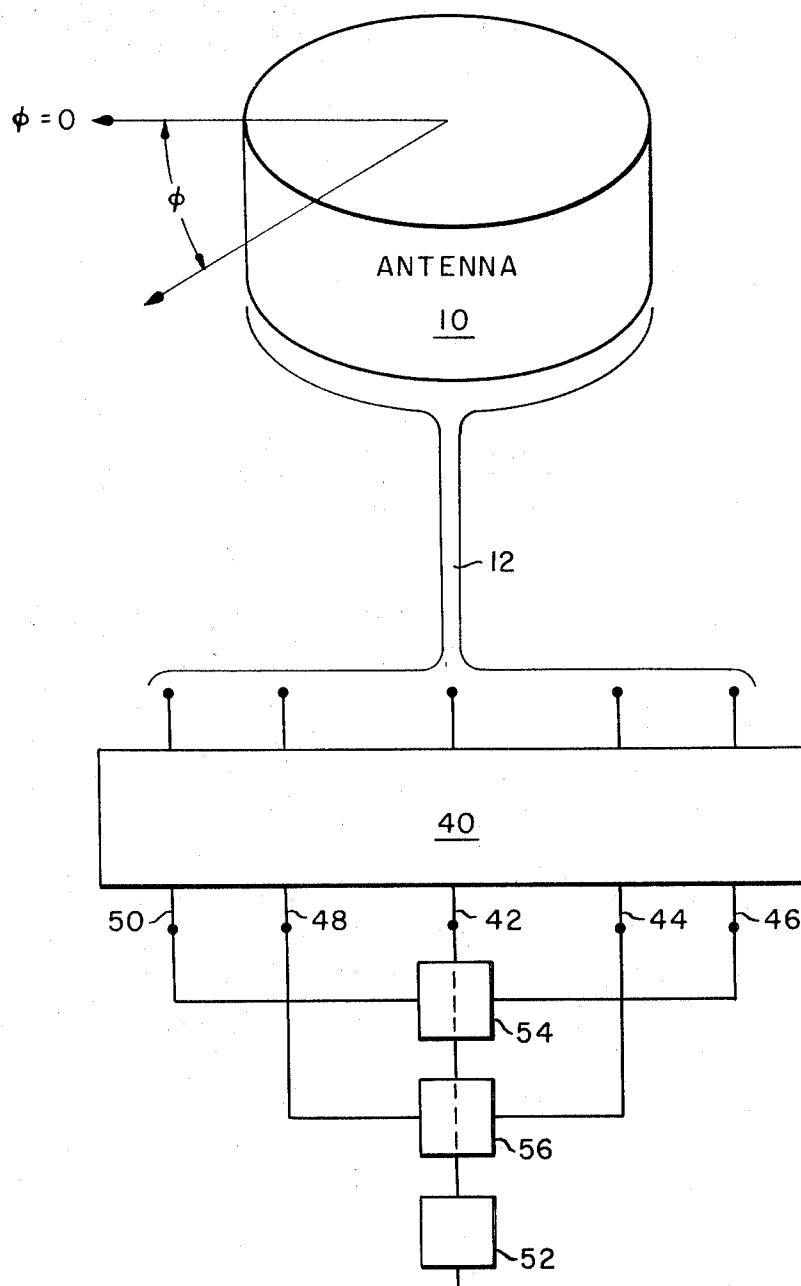


FIG. 3.

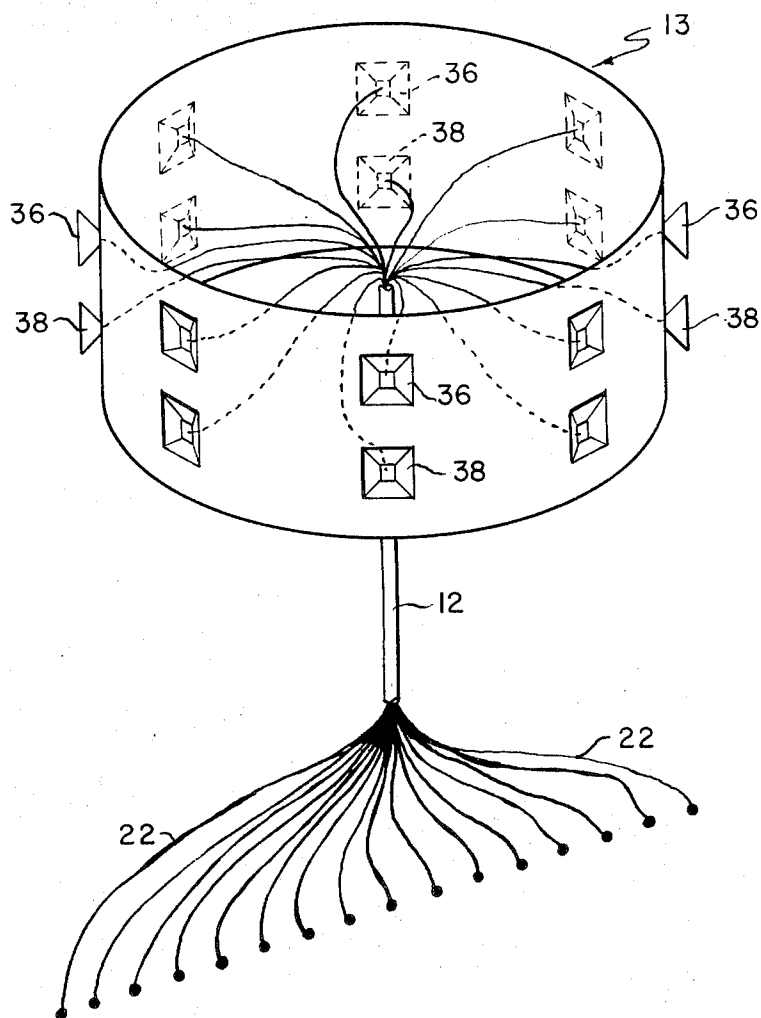


FIG. 4.

CIRCULARLY SYMMETRIC RETRODIRECTIVE ANTENNA

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

The most well known method of obtaining retrodirective beam radiation capability is disclosed by Van Atta in U.S. Pat. No. 2,908,002. Van Atta shows a passive linear array of elements, interconnected in a manner such that an electromagnetic beam is redirected at substantially the same angle from which it came. It has become possible to construct an active Van Atta array, and thus, the use of such an array has been found to be an effective and practical way to obtain retrodirectivity. However, the Van Atta array is basically limited to the linear or planar discrete arrays. Therefore, it effectively lacks the capability of operating with a circularly symmetric array, and is unable to provide 360° coverage. Also, the Van Atta array is not capable of being used with circular continuous aperture antenna systems.

Another method of obtaining retrodirectivity is the fitting of conjugate phase shifters to elements of a circular or linear array. This method is applicable to a general array but is limited in its application because relatively complex circuitry must be provided to each element. Furthermore, an effort must be made to assure that all of the individual circuits are identical with respect to each other so as to provide the desired symmetrical response. Hence, the generation and the control of the return beam is difficult, if not prevented, by this method.

Finally, a modified Van Atta arrangement has been suggested by D. E. N. Davies in Proceedings I.E.E., March 1963. Here, isotropic elements are arranged in a circularly symmetric manner. Although 360° retrodirectivity is possible, problems such as the control of sidelobe level, and the system's size, and weight, preclude the use of this array in many applications. Furthermore, this system is not adaptable to circular arrays arranged around a conducting cylinder.

Considering such drawbacks, I have developed a circularly symmetric retrodirective antenna system which displays none of the disadvantageous conditions set forth above and is capable of either two or three dimensional retrodirectivity.

Although the understanding of this method may be facilitated by referring to the concept of the Van Atta array, the retrodirective properties here are established by a modal phasing technique rather than the principles of interconnecting antenna elements as taught by Van Atta.

SUMMARY OF THE INVENTION

An antenna system having circular symmetry is employed to provide automatic retrodirective performance. Any type of antenna may be selected, as long as it is capable of maintaining substantially linearly varying phase mode sets around the periphery. This type of antenna includes symmetrically spaced elements such as dipoles or spaced slots disposed around a metallic

periphery or even circularly continuous antennas including a biconical horn.

The antenna is connected by way of appropriate transmission line(s) to a multimodal feed network. The network must be able to provide modal phase sets around the entire periphery of the antenna. The mode sets are established by the use of respective mode terminals from the multimodal network. Although a number of multimodal feed networks are acceptable, the Butler matrix or the Blass-Lopez matrix is preferred.

When an electromagnetic signal comes into the circular antenna system on a particular mode from a particular direction, it is then transferred and permitted to leave on an associated mode of the opposite mode sets. Hence, a two or three dimensional retrodirective performance can be created. I have found that active or passive retrodirectivity may be obtained by using multimodal interconnection relationships of the mode sets, while control of the reradiated beam characteristics may be easily provided.

OBJECTS

An object of the invention is to provide an active or passive retrodirective circularly symmetric antenna system.

Another object of the present invention is to provide either two or three dimensional retrodirectivity.

A further object of the present invention is to provide a simple technique for controlling the properties of the reradiated beam.

Another object of the present invention is to provide a retrodirective circular symmetric antenna system wherein the antenna elements may be disposed around a conducting cylinder.

Other objects of the invention will be readily apparent to those skilled in the art by referring to the following detailed description in connection with the accompanying drawing wherein:

THE DRAWING

FIG. 1 illustrates the fundamental components required to obtain retrodirective properties;

FIG. 2 is a particular example of the retrodirective system wherein an even number of mode terminals are employed;

FIG. 3 is another example of the retrodirective system but where an odd number of mode terminals are employed;

FIG. 4 is a diagram of horns mounted on a cylinder in a manner so as to obtain three dimensional retrodirectivity.

DETAILED DESCRIPTION

Referring to FIG. 1, the system includes circular antenna system 10, interconnecting line(s) 12, multimodal feed network 14, network mode terminals 16, and intermode connectors 17.

The antenna 10 may be of a multitude of types including a circular continuous aperture antenna, or an array of discrete radiating elements having circular symmetry; for example, an array of dipoles equally spaced and arranged on a circle, concentric with a conducting cylinder. The selection of any particular antenna system 10 largely depends upon the well known design considerations such as a maximum or minimum size requirement, weight, gain, element spacing, and the other usual requirements. However, any type of

electromagnetic system which has the capability of propagating progressively varying phase functions around the entire periphery, in the far field region, is acceptable for antenna system 10.

The interconnecting lines 12 are employed so as to provide a connection between antenna system 10 and the feed network 14 and are chosen as a result of the selection of the antenna system and the feed network. For example, if the antenna system 10 consists of a biconical horn, the interconnecting line could well be either a coaxial line or a circular wave guide. Similarly if an N element array is selected as the antenna system, the interconnecting line could consist of N number of coaxial cables. The selection of any particular interconnecting line 10 is unimportant to the operation of the entire system as long as the interconnecting line 10 is capable of accurately maintaining amplitude and phase relationship information between the antenna system 10 and the feed network 14.

The feed network 14 is responsible for creating a progressive change in the phase of energy at a constant radius in the far field. If a point at a fixed radius in far field is allowed to vary in angle ϕ , with respect to antenna 10 as shown in FIG. 1, the network 14 must provide a particular phased signal at any particularly defined angle ϕ .

Consider a source of signal applied to a particular mode terminal of the feed network 14. As ϕ is swept around the periphery in a counter clockwise direction starting from $\phi = 0$, the phase of the signal increases from 0° to 360° or multiples of 360° as the ϕ revolution is complete. That is, when ϕ returns to 360° , a particular phased mode is established around the antenna.

The particular mode which is being energized may be determined by measurements taken in the far field. This is accomplished by noting the number of times the signal increases in phase by 360° as ϕ varies from 0° to 360° . For example, if ϕ is swept from 0° to 360° and the value of the phased signal remains at 0° around the entire periphery, mode 0 is present. If, however, ϕ is varied from 0° to 360° and the value of the phased signal correspondingly changes from 0° to 360° , mode 1 is present. Similarly, if 100 varies from 0° to 360° and the value of the phased signal changes from 0° through 360° to 720° , mode 2 is present.

An associated mode set must also be provided by the feed network 14 and such is denoted by a negative sign before the mode number. Hence, considering mode (-2) for example, when ϕ varies from 0° to 360° , the value of the phased signal changes from 0° through -360° to -720° in a manner complementary to mode 2. Obviously only whole (integer) modes are desirable for the positive and negative mode sets, and for the purpose of this description mode 0 is included in the negative mode set when considering an even number of mode terminals.

The superposition of a number of modes may be used to provide a constructive interference pattern to produce a directive main beam centered around $\phi = \phi_0$ in the far field. In addition, the destructive interference resulting from the superposition is used to assure a relative absence of radiation in all but the main beam direction.

Thus, any type of multi-modal feed network 14 which is capable of producing the above recited phase properties is acceptable as long as it is able to properly match with the selected antenna structure 10. For example, if

the antenna system 11 is a symmetrical array of N elements 20 mounted on metallic cylinder 18 as shown in FIG. 2, and the connecting line 12 is N number of coaxial cables 22, the feed network could be an (N x N) Butler matrix 24 such as those disclosed in Chapter III of R. C. Hansen's "Microwave Scanning Antennas" Vol. 3, 1966. If it is needed, each coaxial cable may be connected through a fixed phase shifter (not shown) to the matrix to assure that all modes are in phase in a particular direction such as $\phi = 0^\circ$.

The mode terminals 16 of the feed network 14 control the modes in the two mode sets and are an integral part thereof. Therefore, as is true in the Butler matrix or Blass-Lopez, the selected network must have the ability to establish mode n or mode (-n) around the antenna system when a unit amplitude voltage is respectively applied to mode terminal n or mode terminal (-n).

Under this condition the far field radiation pattern as a function of ϕ is in the form:

$$\vec{E}_n(\phi) = A_n \exp[jn\phi],$$

where n is any mode of either the positive or negative mode set, and A_n is the relative gain of mode n. The far field radiation pattern as shown in Eq. (1) is of course taken in the plane normal to the longitudinal axis of the antenna system, and usual terms involving distance and frequency are omitted. Thus, Eq. (1) represents an omnidirectional pattern with the phase varying linearly with the far field angle ϕ .

Consider a unit amplitude electromagnetic plane wave incident upon the antenna system 10 from a particular direction namely $\phi = \phi_0$. Referring to Eq. (1) and applying the law of reciprocity yields a voltage, $\vec{S}_n$ in FIG. 2, at mode terminal n of the feed network 14 in FIG. 1, or the Butler matrix 24 in FIG. 2 in the form:

$$\vec{S}_n = A_n \exp[jn\phi_0].$$

When the mode terminals of the positive mode set are properly interconnected to the terminals of the negative mode set, using equal electrical length transmission lines such as lines 17 in FIG. 1, a beam will radiate from antenna system 10 in the direction of $\phi = \phi_0$.

That is to say, the plane wave comes in on mode n from a direction $\phi = \phi_0$ to the antenna system 10 (Eq. 1), passes through the feed network 12, and appears as a voltage on mode terminal n (Eq. (2)). If mode terminal n is connected to an associated terminal of the opposite mode set, for example terminal (1-n) as shown in FIG. 1 when there are an even number of terminals employed, the signal will pass back through the feed network 14 and will reradiate on mode (1-n) of the antenna 10. The reradiation is in the form:

$$\vec{E}_{(1-n)}(\phi) = A_n A_{(1-n)} \exp[jn\phi_0] \exp[j(1-n)\phi].$$

Considering a complementary case where a signal comes into the antenna system 10 on mode (1-n), it will reradiate on mode n:

$$\vec{E}_n(\phi) = A_n A_{1-n} \exp[j(1-n)\phi_0] \exp[jn\phi].$$

Setting $\phi = \phi_0$ in Eq. (3) and Eq. (4) gives the immediate result:

$$\vec{E}_n(\phi_0) = \vec{E}_{(1-n)}(\phi_0) = A_n A_{(1-n)} \exp[jn\phi_0].$$

As can readily be seen, Eq. (5) demonstrates that all modes in both the positive and negative mode sets (mode 0 included in the negative set) are in phase in the direction of $\phi = \phi_0$, hence a beam will be radiated in the ϕ_0 direction as long as the intermodal connecting lines 17 are of equal electrical length.

The above description has considered a circularly symmetric array of an even number of elements. However, certain matrices which are capable of feeding arrays having an odd number of elements do exist, and the selection of any particular matrix should be consistent with the principles described above. Also, in the above example, all modes of an available even number of modes were utilized. This is not a restriction, however, since an odd number of modes, selected from the available even number, may be utilized as will be explained below.

A requirement of most practical antenna systems is the ability to control the beam pattern characteristics at far field. In the passive system, shown in FIG. 1, the use of simple transmission lines provide minimal control of the reradiated beam characteristics. Slightly more control may be obtained by choosing not to interconnect selected associated mode pairs. These non-connected mode terminals would simply be terminated in matched loads. However, if each of the modes in the two mode sets are individually connected to the mode terminals of the opposite set, individual adjustment networks 28, 30, 32, and 34 as shown in FIG. 2 can be connected into the individual intermodal connecting lines. The network provides a simple means for inserting well known devices such as a modulator, encoder, or frequency translators. If G_n is the gain of the adjustment network as developed from mode n , and $G_{(1-n)}$ is the gain of the network as developed from mode $(1-n)$, Eq. (3) and Eq. (4) respectively become:

$$\vec{E}'_n(\phi) = G_n A_n A_{(1-n)} \exp[j(1-n)\phi_0] \exp[jn\phi]$$

and;

$$\vec{E}'_{(1-n)}(\phi) = G_{(1-n)} A_n A_{(1-n)} \exp[jn\phi_0] \exp[j(1-n)\phi].$$

Letting $\phi = \phi_0$, Eq. (6) becomes:

$$\vec{E}'_n(\phi_0) = G_n A_n A_{(1-n)} \exp(j\phi_0),$$

and Eq. (7) becomes:

$$\vec{E}'_{(1-n)}(\phi_0) = G_{(1-n)} A_n A_{(1-n)} \exp(j\phi_0).$$

It should be apparent from Equation (8) and Equation (9) that the phase of $\vec{E}'_n$ equals the phase of $\vec{E}'_{(1-n)}$;

thus providing the retrodirective properties while allowing individual adjustments of the various modes to affect the reradiation in the far field. These adjustments are provided by merely selecting the respective gains ($G_n, G_{(1-n)}$) of the networks 28, 30, 32 and 34.

Perhaps the most useful and convenient method of obtaining retrodirectivity from a circularly symmetric system occurs when an odd number of mode terminals are employed from the multimodal feed network. Referring to FIG. 3, a multimodal feed network, such as a Butler matrix 40, is connected to a circular symmetric antenna structure 10 via line(s) 12 and is shown to have five mode terminals 42, 44, 46, 48, and 50. Although the total number of odd mode terminals is unimportant (i.e., 3, 5, 7, . . .) in the understanding of the principle of operation, the selection of the number of odd terminals which produce a desired side lobe level and beam shape should be balanced against the number of gain networks such as 54 and 56 which one desires to use.

As shown in FIG. 3, mode terminal 42 may be considered the center mode with an equal number of modes disposed on each side. Namely, modes 44 and 46 constitute the positive mode set and modes 48 and 50 the negative mode set. For the purpose of this discussion involving a specific odd number of mode terminals, mode 0 becomes the center mode and no longer can be considered part of the negative mode set. Therefore, the device in FIG. 3, may be viewed upon as having three particular mode sets, namely the positive mode set (44, 46), the negative mode set (48, 50), and center mode set (42) which consists of one member. I have found that a symmetrical response, which is easily analyzed, appears in the far field when the positive mode set is interconnected to the negative mode set (i.e. the connection of mode terminal n to $(-n)$) and the center mode set is connected to itself. Thus, connecting mode n to mode $(-n)$ gives:

$$\vec{E}_n(\phi) = A_n A_{(-n)} \exp[jn\phi_0] \exp[-jn\phi]$$

and;

$$\vec{E}_{(-n)}(\phi) = A_n A_{(-n)} \exp[-jn\phi_0] \exp[jn\phi]$$

By the same procedure used for Eq. (3) and Eq. (4), Eq. (10) and Eq. (11) may be combined by setting $\phi = \phi_0$. As an analogy to Eq. (5), retrodirective properties will therefore result. Also the control characteristics obtained by G_n and $G_{(-n)}$ are analogous to the control provided by Eq. (8) and (9) and are obtainable by way of networks 52, 54, and 56.

The positive-negative mode interconnections may be either active or passive and each should have an equal electrical length of l . The center mode interconnection may be an open circuited line of length $l/2$ in the passive system or may include gain network 52 in the active system. The retrodirective response has a maximum at $\phi = \phi_0$ and is an even function and therefore symmetric about ϕ_0 . By employing the notation as previously set forth, the total far field reradiation can be easily shown as a function of ϕ :

$$\vec{E}(\phi) = G_0 A_0^2 + 2 \sum_{n=1}^P G_n A_n^2 \cos[n(\phi - \phi_0)], \quad (12)$$

where;

$P = \frac{1}{2} [\text{Total No. of Modes} - 1]$, and; $G_n = G_{(-n)}$, and
 $A_n = A_{(-n)}$.

The method described thus far has been in relation to two-dimensional retrodirectivity. However, three dimensional retrodirectivity performance is also possible by extending the principles of this invention.

The array of M circular antenna systems in the form of rows as shown in FIG. 4 when $M = 2$, can be of any type although FIG. 4 depicts pyramidal horns such as 36 and 38. The pyramidal horns are equally spaced around cylindrical casing 13 in rows. Each element is connected to an individual coaxial cable such as cable 22 to form the interconnecting line 12. The individual cables are then connected to a multi-modal feed network such as a Butler matrix.

The n^{th} mode terminal on the m^{th} circular antenna row is labeled $T_{n,m}$, the following scheme of modal interconnection will result in three dimensional retrodirectivity:

$[T_{n,m}]$ connected to $[T_{(1-n), (M-m+1)}]$.

Obviously this modal interconnection scheme is only one of the many which are possible. However, any scheme is satisfactory as long as it is selected in accordance with the teachings and equations herein. Also, the three dimensional circularly symmetric antenna system is also capable of active or passive performance.

Obviously many modifications and variations of the present invention are possible in light of the above teachings. For example, the teachings described herein regarding electromagnetic waves equally applies to the analogous structure in acoustics. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed and desired to be secured by letters patent of the United States is:

1. A method of providing retrodirectivity properties from a circular symmetric antenna system comprising: receiving a wavefront from a ϕ_0 direction, the antenna system being capable of maintaining substantially linearly varying phase mode properties around the antenna periphery;
 converting said wavefront into a corresponding first set of signals while maintaining amplitude and phase relationships of said first set of signals wherein the phase mode set is defined a set of n modes, each of which is a linear variation in phase around the antenna's periphery such that for the n^{th} mode of the set the phase changes by $n \times 360$ electrical degrees as the angle ϕ changes by 360° around the antenna's periphery;
 transposing said first set of signals into a first phase mode set with a multimodal network such that said first phased mode set provides a plurality of voltages to mode terminals corresponding to said first set of signals;
 interconnecting said mode terminals into associated mode terminals corresponding to a second mode set;
 reconverting said second mode set into a corresponding second set of signals;

applying said second set of signals to the antenna such that a wavefront is generated to the ϕ_0 direction.

2. A circular symmetric retrodirectivity antenna system comprising:
 circular symmetric antenna means; and
 multimodal feed network means having an even plurality of n mode terminals wherein $n/2$ mode terminals provide for a first phased mode set, and the remainder of said n mode terminals provide for an associated phased mode set, said multimodal feed network having the characteristic that if a unit voltage is applied to mode terminal n , the far field radiation pattern, $\vec{E}(\phi)$, is in the form

$$\vec{E}_n(\phi) = A_n \exp jn\phi$$

where A_n is the relative gain of mode n and ϕ is any selected angle;

coupling means for coupling said antenna means to said feed network means such that the first phased mode set and said associated mode set are able to be established around the periphery of the antenna means; and

intermodal connecting means for connecting a part of said $n/2$ mode terminals to an equal part of said remainder of said n mode terminals to effect selected mode pairs such that when a wavefront is presented to said antenna means retrodirectivity subsequently results therefrom.

3. The retrodirectivity antenna system as claimed in claim 2 wherein said multimodal feed network is a Butler matrix.

4. The retrodirectivity antenna system as claimed in claim 2 wherein said intermodal connecting means comprises: passive lines each of a length l .

5. The retrodirectivity antenna system as claimed in claim 4 wherein gain networks are disposed in the passive lines.

6. The retrodirectivity antenna system as claimed in claim 2 wherein said antenna means comprises a plurality of individual elements.

7. The retrodirectivity antenna system as claimed in claim 6 wherein said individual elements are dipoles and are disposed around a conducting cylinder.

8. The system as claimed in claim 7 wherein gain networks are disposed in each of the passive lines of length l .

9. The system as claimed in claim 8 wherein a gain network is disposed in the open circuit center mode line.

10. A circular symmetric retrodirectivity antenna system comprising:

circular symmetric antenna means;
 multimodal feed network having a center mode set consisting of one center terminal; a positive mode set and a negative mode set each having n terminals, said multimodal feed network having the characteristic that if a unit voltage is applied to mode terminal n , the far field radiation pattern, $\vec{E}(\phi)$, is in the form

$$\vec{E}_n(\phi) = A_n \exp jn\phi$$

where A_n is the relative gain of mode n and ϕ is any selected angle;

coupling means for coupling said antenna means to said feed network such that the center, positive and

negative mode sets are able to be established around the periphery of the antenna means;
 intermodal connecting means for interconnecting a portion of the n terminals of the positive mode set to an equal number of terminals in the negative mode set; and an open circuit line connected to said center mode terminal;
 so that when a wavefront is presented to the antenna means, retrodirectivity results.

11. The system as claimed in claim 10 wherein said multimodal network comprises:
 a Butler matrix.

12. The system as claimed in claim 10 wherein said intermodal connecting means comprises:
 passive lines, each of a length l , and said open circuit line is of length $l/2$.

13. The system as claimed in claim 10 wherein said antenna means comprises:
 a plurality of radiators.

14. The system as claimed in claim 13 wherein said radiators are dipoles disposed around a conducting cylinder.

15. A circular symmetric retrodirective antenna system comprising:

circular symmetric antenna means; and
 Butler matrix network means having an even plurality of n mode terminals wherein $n/2$ mode terminals provide for a first phased mode set, and the remainder of said n mode terminals provide for an associated phased mode set, said Butler matrix having the characteristic that if a unit voltage is applied to mode terminal n , the far field radiation pattern, $\vec{E}(\phi)$, is in the form

$$\vec{E}_n(\phi) = A_n \exp jn\phi$$

where A_n is the relative gain of mode n and ϕ is any selected angle;

coupling means for coupling said antenna means to said feed network means such that the said first phased mode set and said associated phased mode set are able to be established around the periphery of the antenna means; and

intermodal connecting means for connecting a part of said $n/2$ mode terminals to an equal part of said remainder of said n mode terminals to effect selected mode pairs such that retrodirectivity results from said antenna means.

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