United States Patent [19]

Stangel et al.

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[45] **Aug. 28, 1973**

[54] PHASED ARRAY FED LENS ANTENNA

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[73] Assignee: **Sperry Rand Corporation,** New York, N.Y.

[22] Filed: **Dec. 20, 1971**

[21] Appl. No.: **209,863**

[52] **U.S. Cl.** .... **343/100 SA,** 343/754, 343/854, 343/911

[51] **Int. Cl.** **H04b 7/00**

[58] **Field of Search** .... 343/100 SA, 753, 343/754, 854, 909, 911 R

[56] **References Cited**

UNITED STATES PATENTS

2,795,783	6/1957	Dunbar	343/911 R
3,631,503	12/1971	Tang et al.	343/854
3,444,559	5/1969	Mumford	343/854
3,413,636	11/1968	Migdal	343/911 R
3,245,081	4/1966	McFarland	343/754

Primary Examiner—Benjamin A. Borchelt
Assistant Examiner—S. C. Buczinski
Attorney—Howard P. Terry

[57] **ABSTRACT**

A phased array antenna functions as a source of electromagnetic energy directed toward a non-planar lens positioned in the near field of the phased array antenna. The non-planar lens includes a plurality of modules comprised of collector elements, phase shifter elements and radiator elements. Electromagnetic energy radiated from the feed antenna to the plurality of collector elements in the non-planar lens is coupled from the collector elements through the phase shifter elements to the radiating elements. Each phase shifter has a fixed delay which acts upon the electromagnetic energy transmitting through the phase shifter so that the electromagnetic energy radiated by the associated radiating element combines with the radiated energy from the other radiating elements to produce a beam having a modified scan angle relative to the scan angle of the emitted beam from the phased array antenna.

20 Claims, 23 Drawing Figures

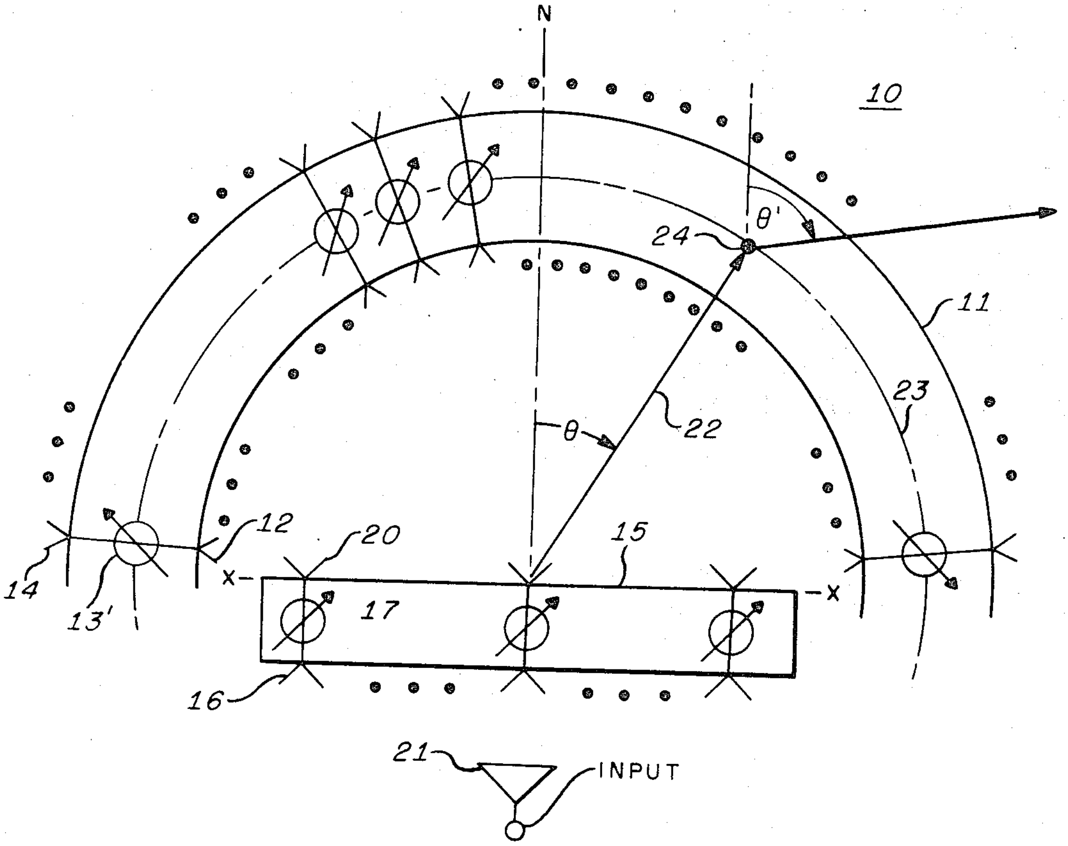
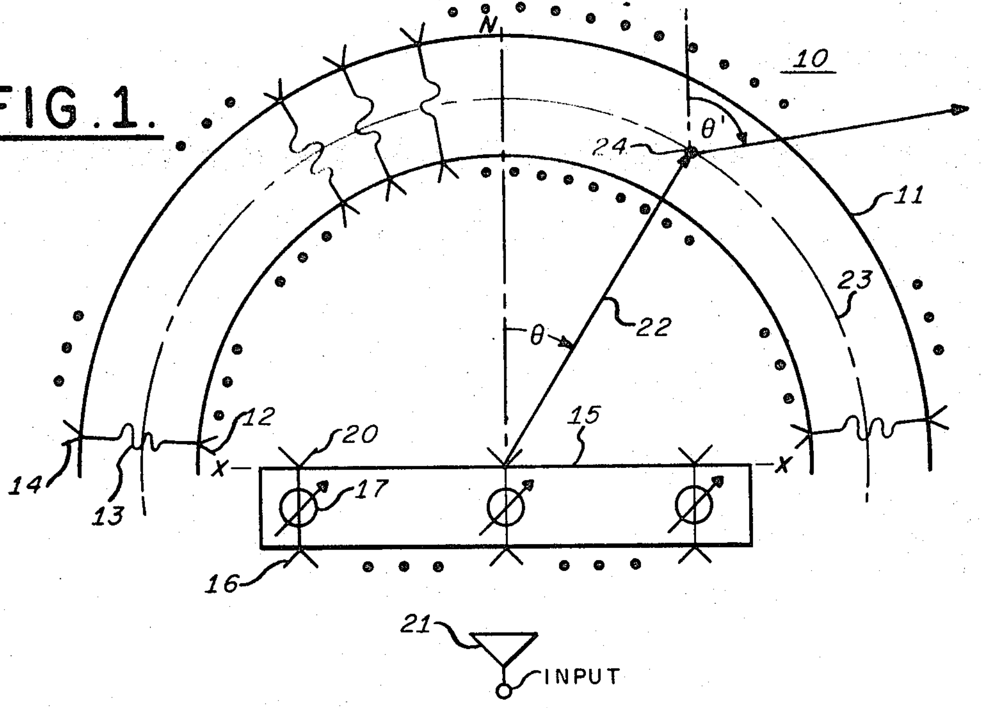


FIG. 1.



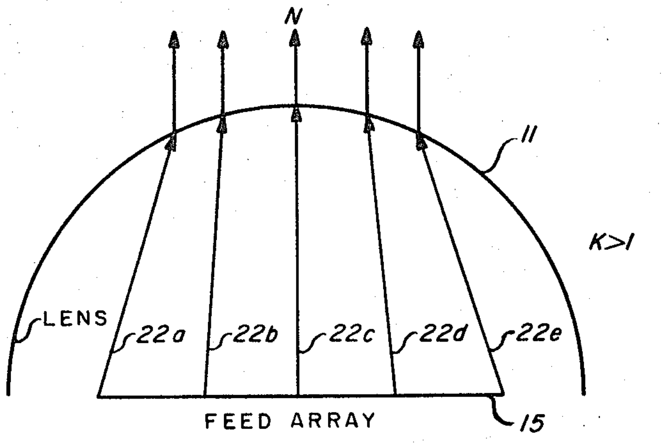


FIG. 2a.

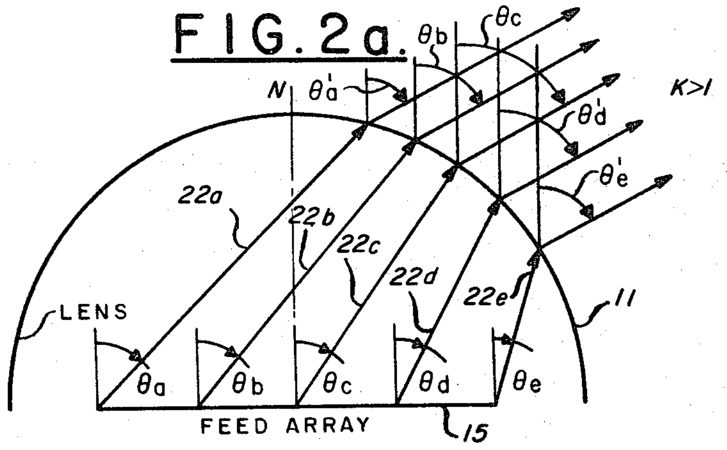


FIG. 2b.

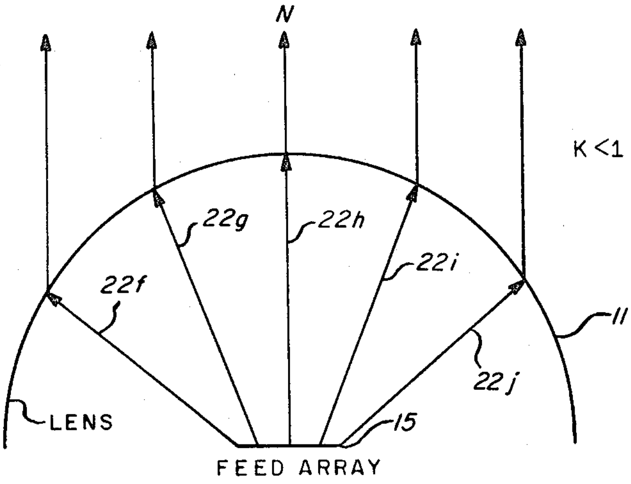

N
K <1
22g
22h
22f
22i
11
22j
LENS
15
FEED ARRAY

FIG. 3a.

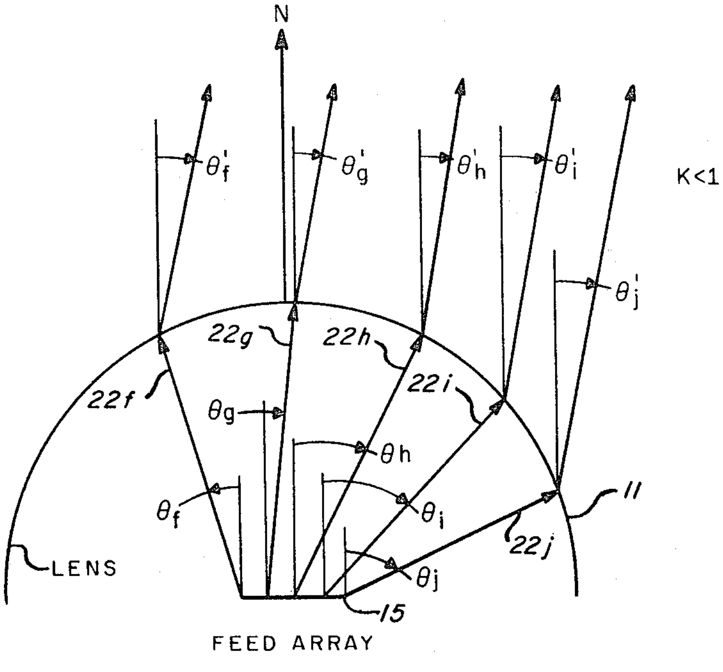

N
θ'_f
θ'_g
θ'_h
θ'_i
K<1
θ'_j
22g
22h
22f
22i
θ_g
θ_h
θ_f
θ_i
11
22j
LENS
θ_j
15
FEED ARRAY

FIG. 3b.

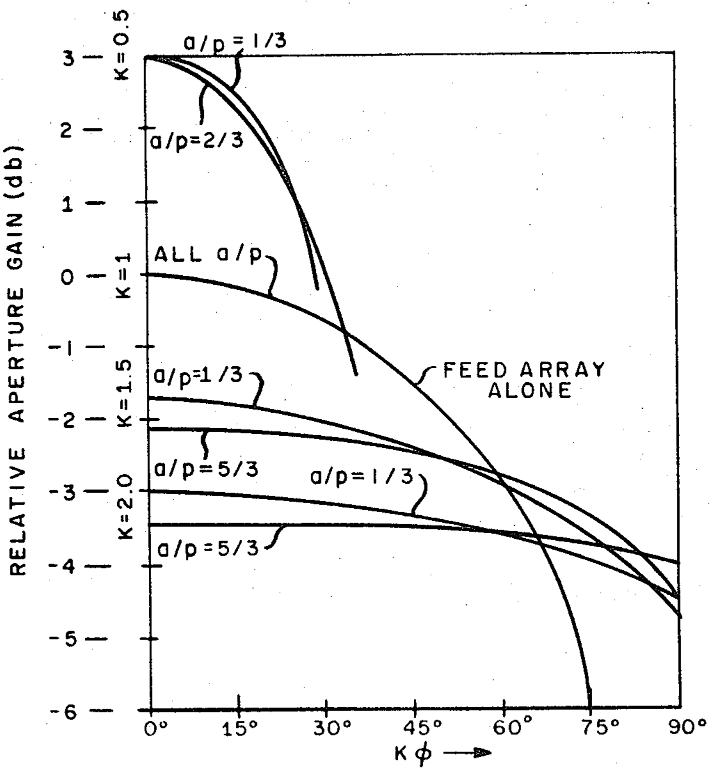

K=0.5
a/p = 1/3
a/p=2/3
ALL a/p
K=1
FEED ARRAY ALONE
a/p=1/3
K=1.5
a/p=5/3
a/p=1/3
K=2.0
a/p=5/3
RELATIVE APERTURE GAIN (db)
3
2
1
0
-1
-2
-3
-4
-5
-6
0°
15°
30°
45°
60°
75°
90°
Kφ →

FIG. 4.

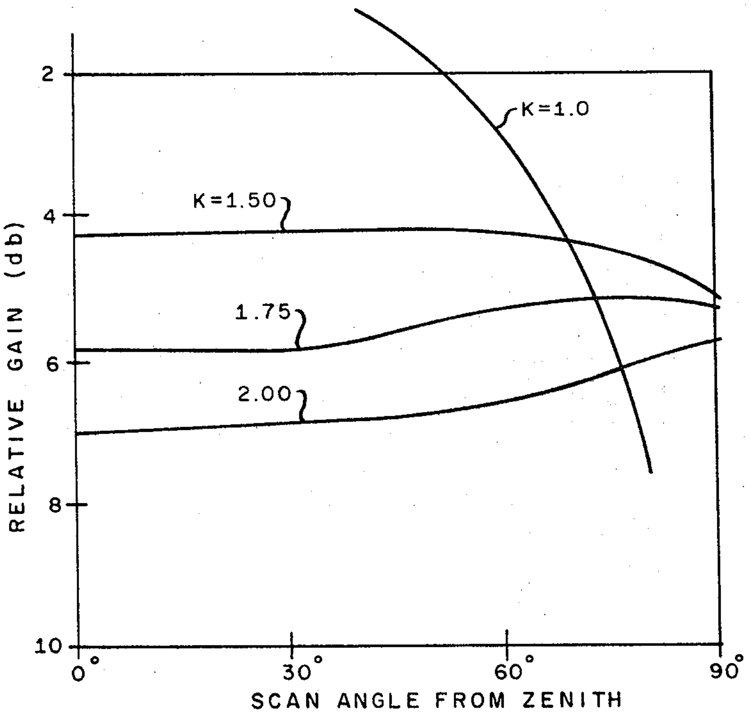

K=1.0
K=1.50
1.75
2.00
RELATIVE GAIN (db)
2
4
6
8
10
0°
30°
60°
90°
SCAN ANGLE FROM ZENITH

FIG. 5.

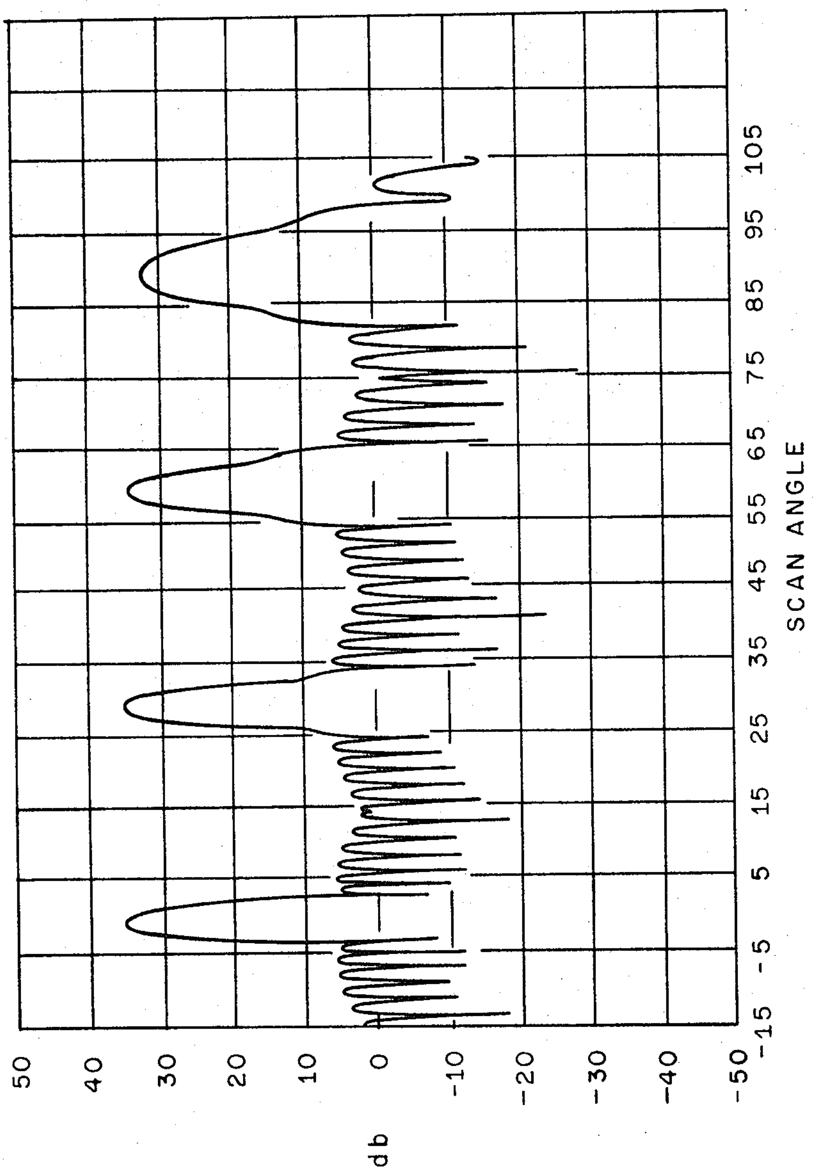

50
40
30
20
10
0
-10
-20
-30
-40
-50
db
-15
-5
5
15
25
35
45
55
65
75
85
95
105
SCAN ANGLE

FIG.6.

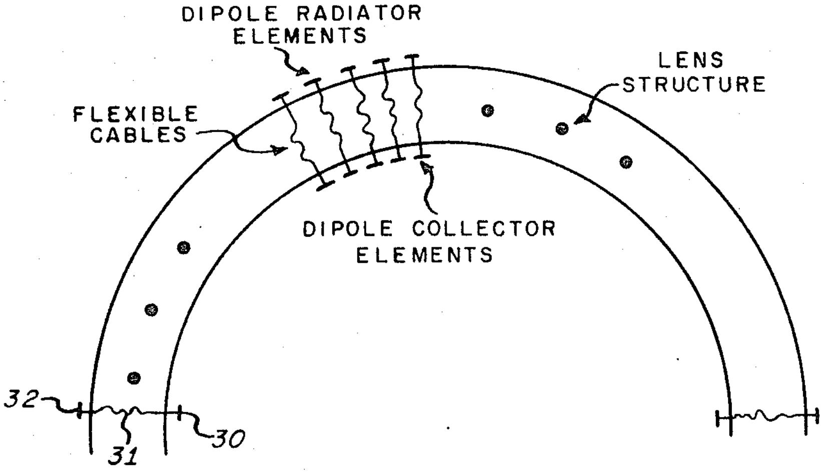

DIPOLE RADIATOR ELEMENTS
LENS STRUCTURE
FLEXIBLE CABLES
DIPOLE COLLECTOR ELEMENTS
32
31
30

FIG. 7.

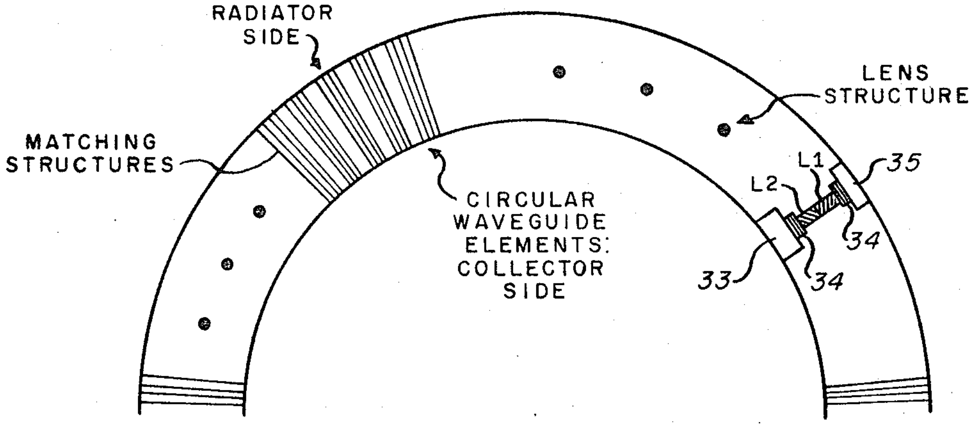

RADIATOR SIDE
MATCHING STRUCTURES
LENS STRUCTURE
CIRCULAR WAVEGUIDE ELEMENTS: COLLECTOR SIDE
L1
L2
35
34
33
34

FIG. 8.

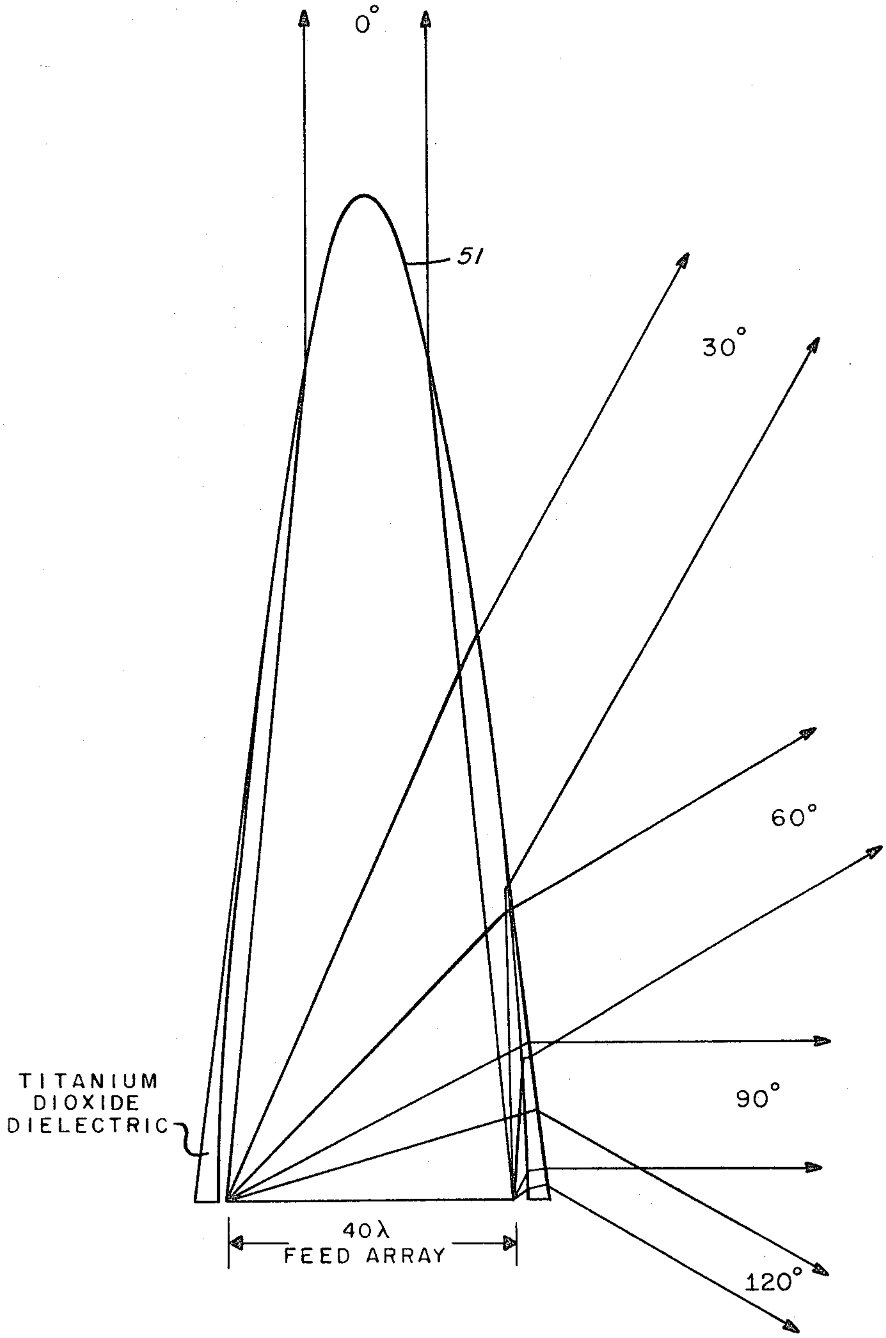


FIG. 9.

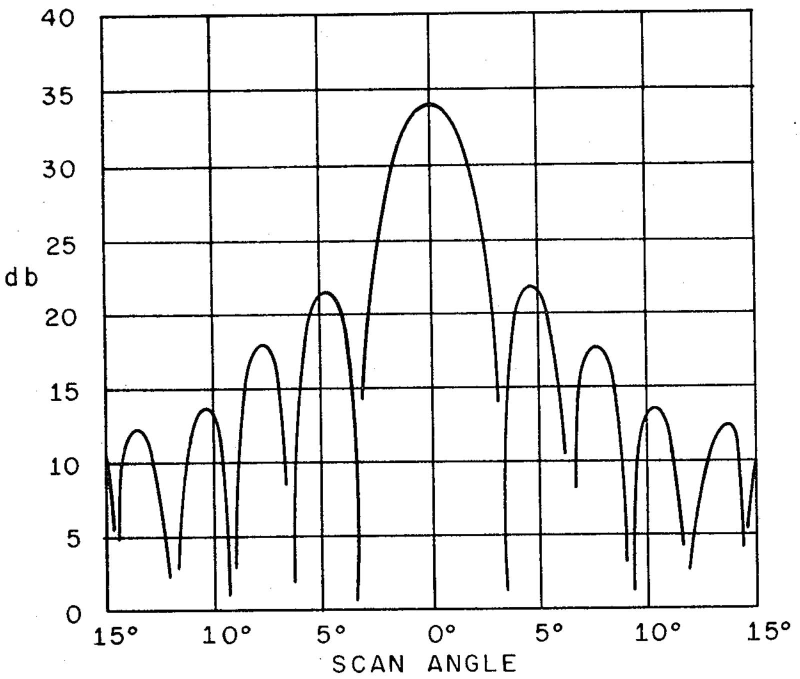


FIG.10a.

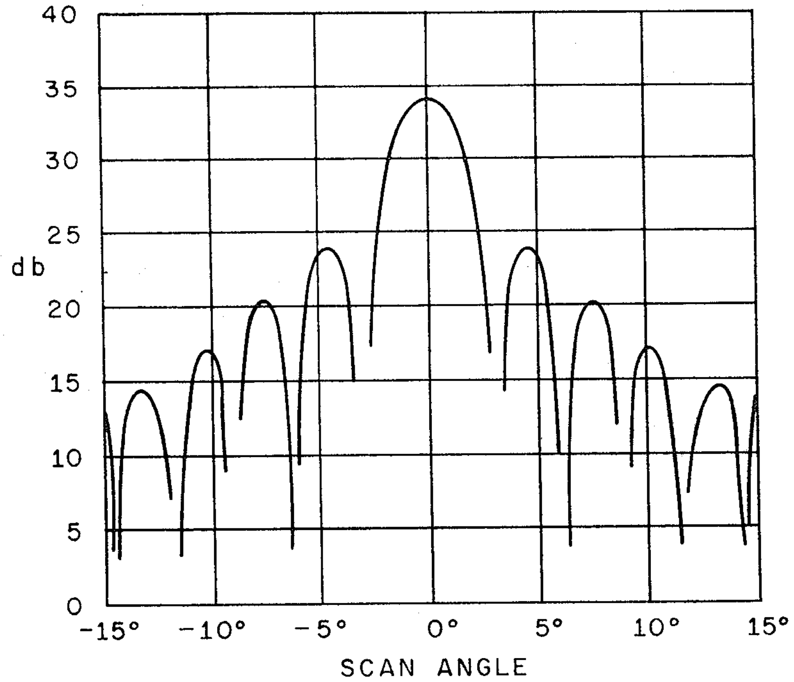


FIG.10b.

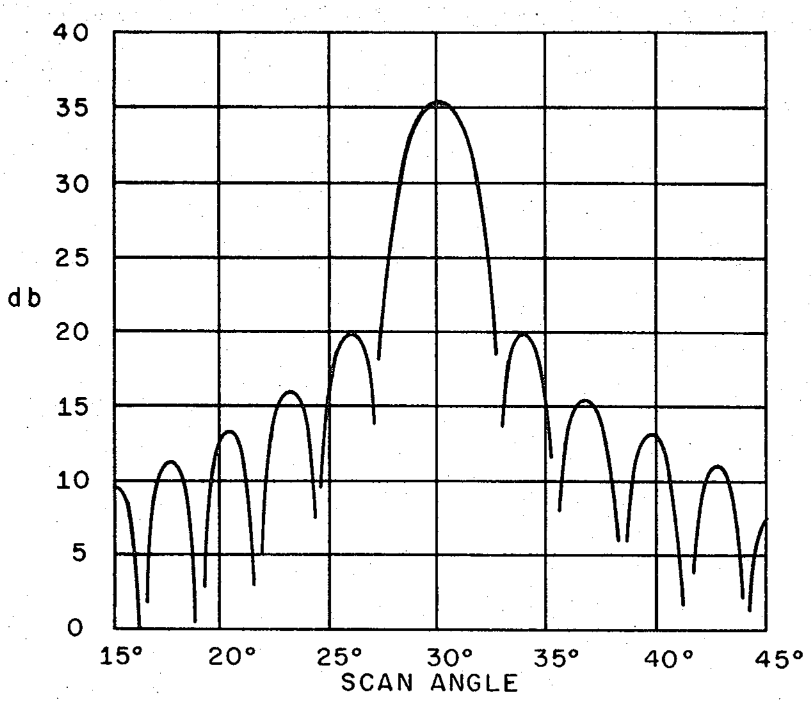


FIG.10c.

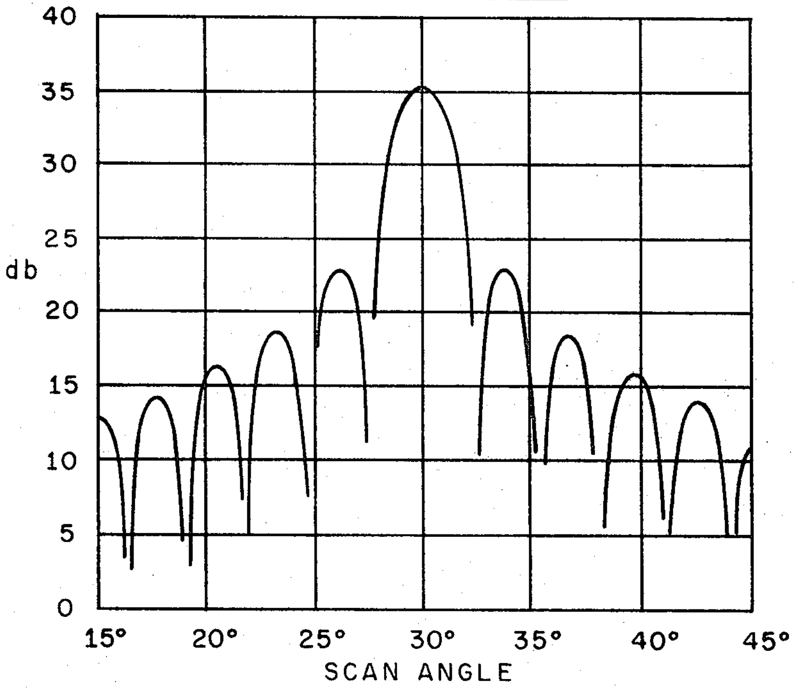


FIG.10d.

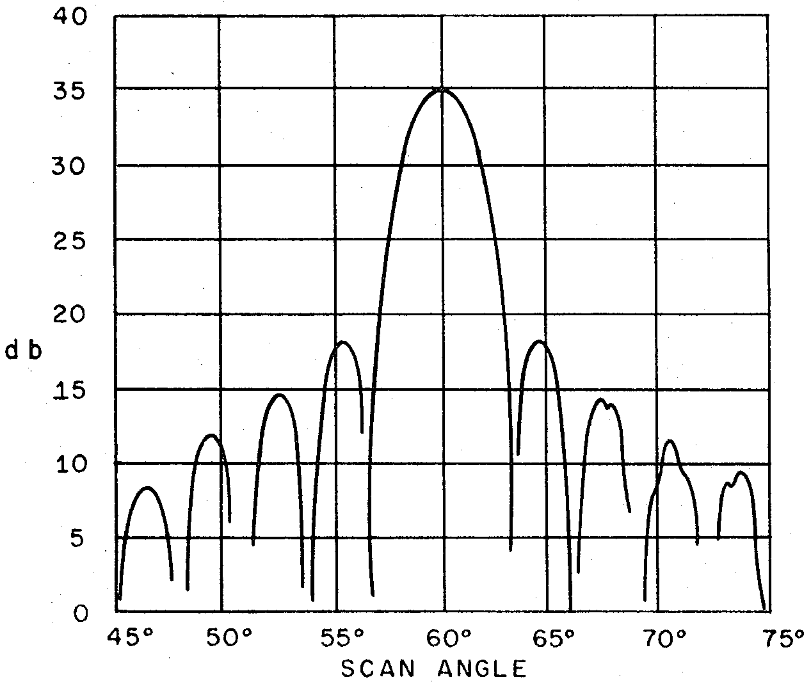


FIG.10e.

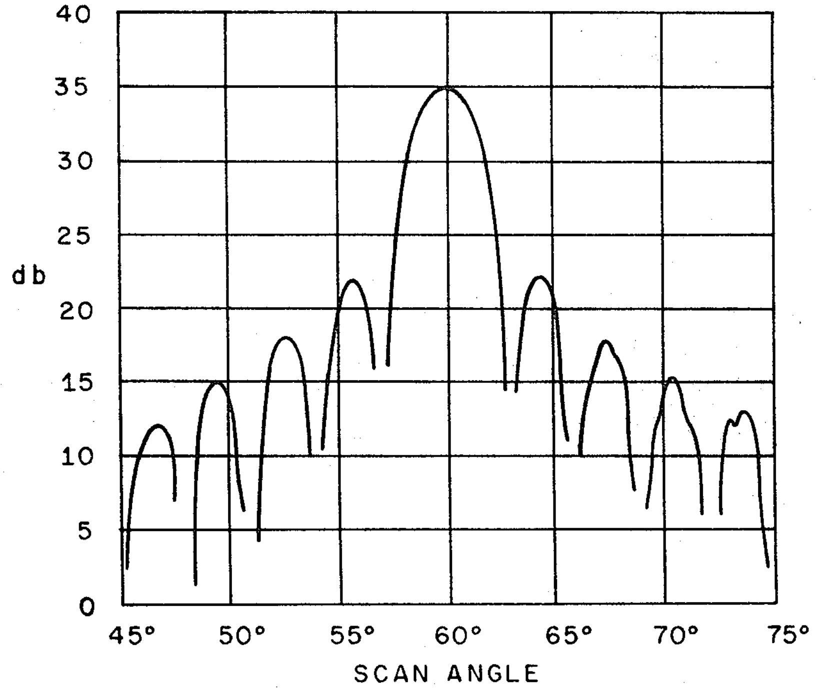


FIG.10f.

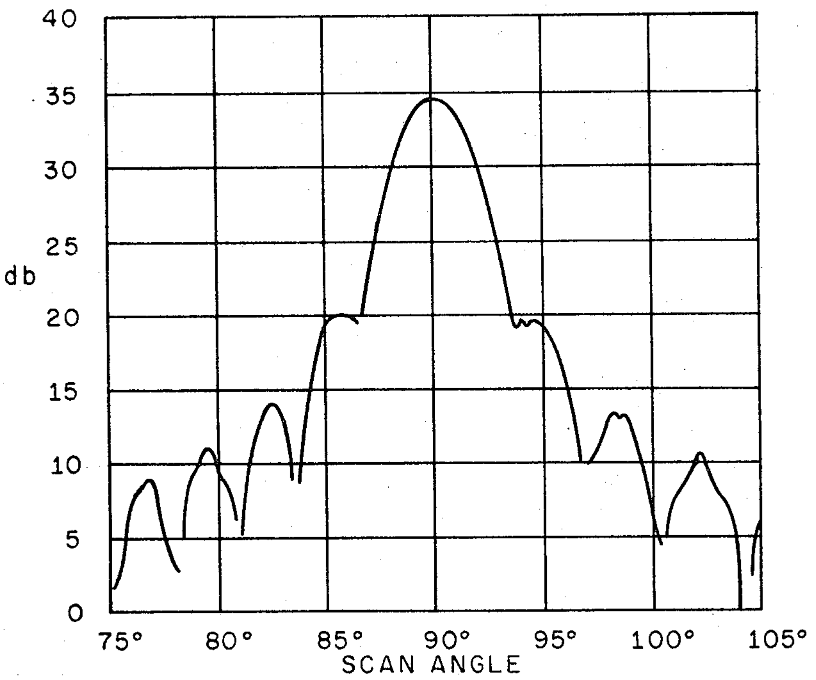


FIG. 10g.

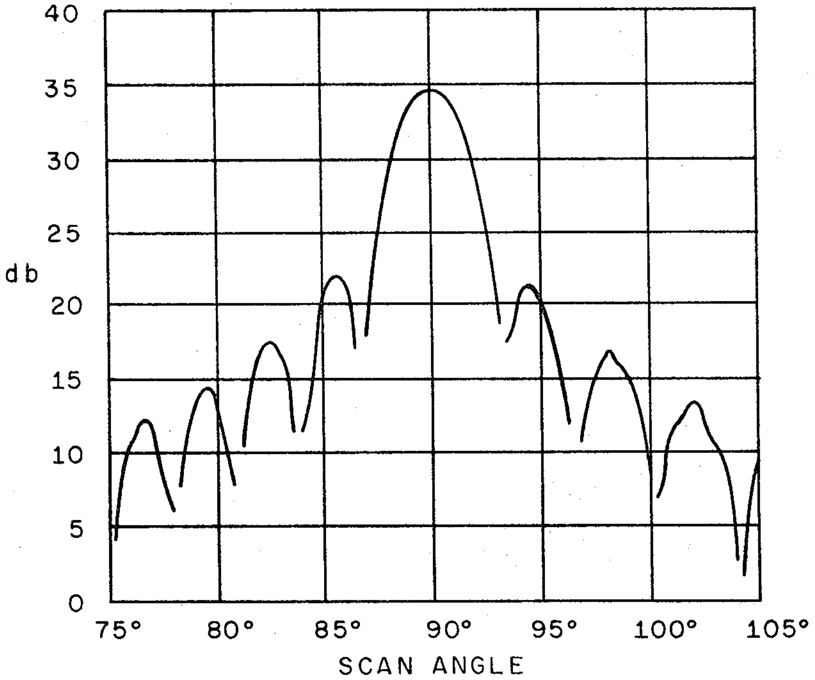


FIG. 10h.

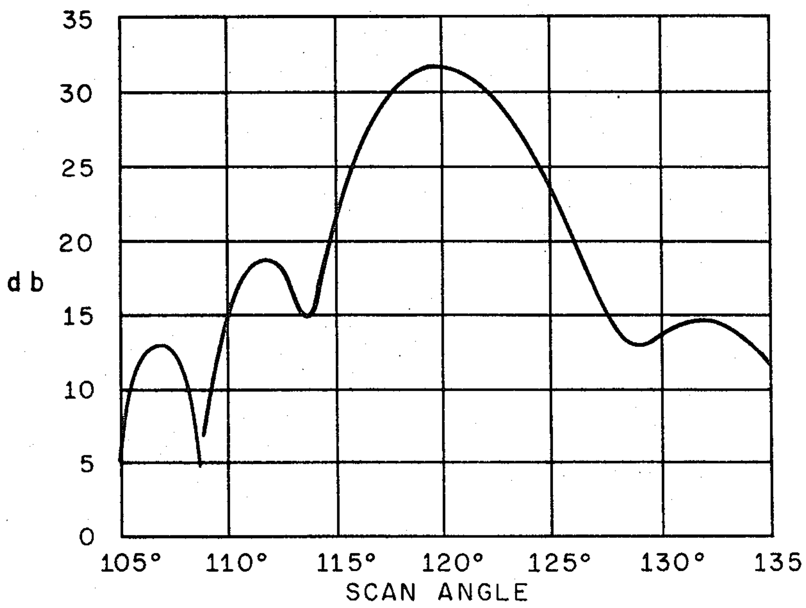


FIG. 10i.

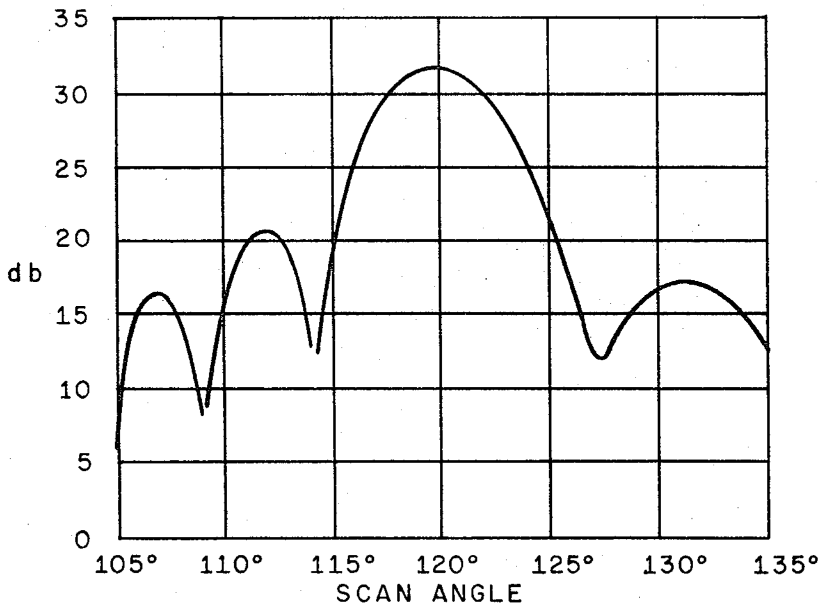


FIG. 10j.

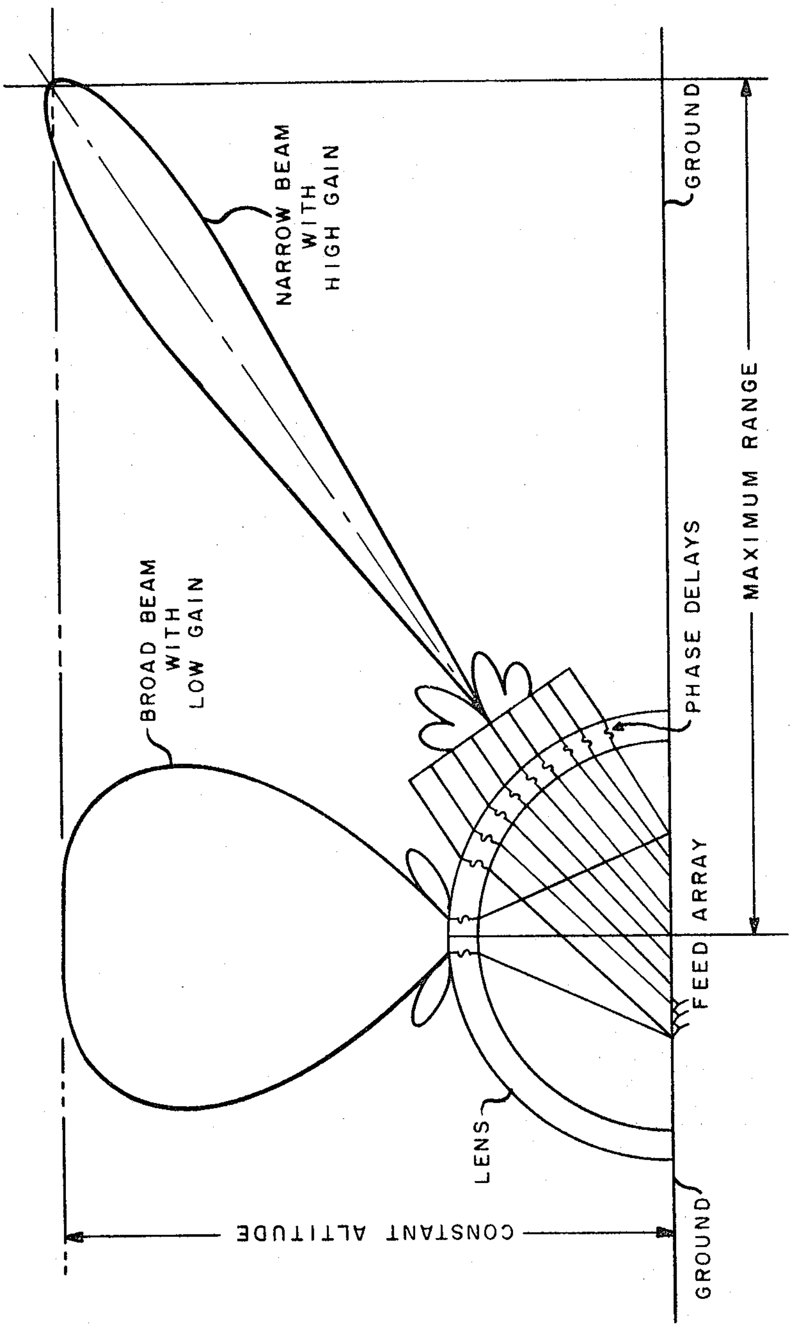

NARROW BEAM
WITH
HIGH GAIN
GROUND
MAXIMUM RANGE
PHASE DELAYS
ARRAY
FEED
BROAD BEAM
WITH
LOW GAIN
LENS
CONSTANT ALTITUDE
GROUND

FIG. 11.

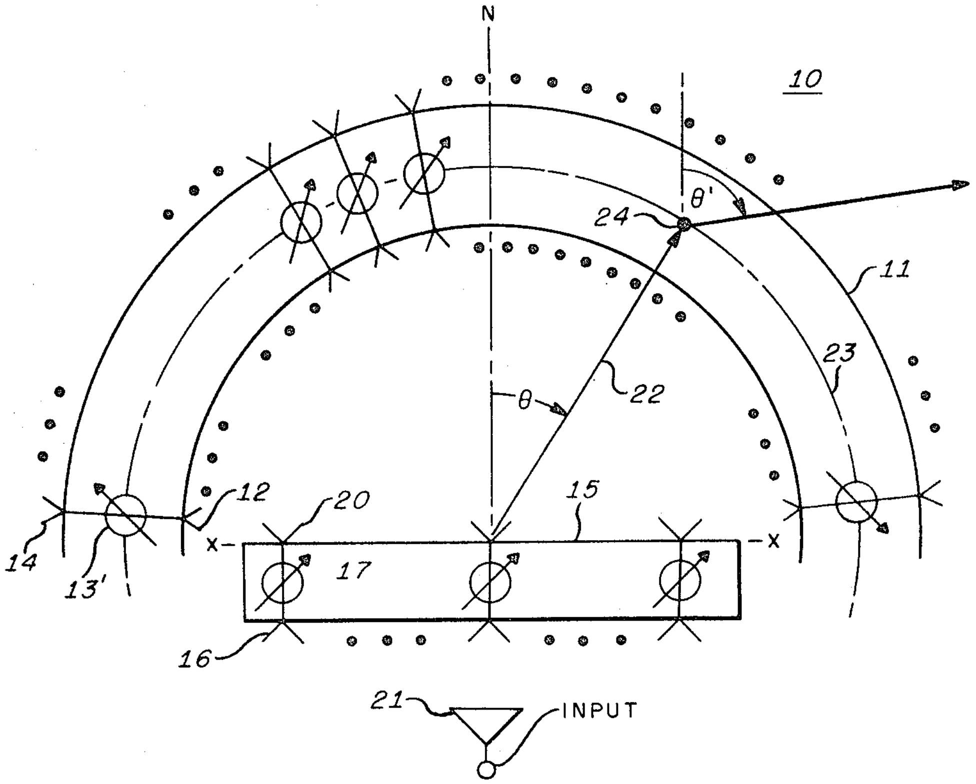


FIG.12.

PHASED ARRAY FED LENS ANTENNA

BACKGROUND OF THE INVENTION

1. Field of the Invention

The subject invention pertains to the art of antennas and specifically to a combination antenna which includes a phased array antenna and a lens antenna.

2. Description of the Prior Art

In many of the early antennas that were developed for radars before World War II array antennas were used at relatively low frequencies, i.e., VHF or low UHF. However, with the advent of microwave radar and the application of optical techniques to microwave frequencies, interest in array antennas declined while interest centered on reflector antennas and lenses. These types of antennas were easier to design, simpler to manufacture and proved sufficiently reliable in operation.

In the last decade interest has been refocussed on array antennas, particularly phased array antennas because the speed of potential targets has greatly increased and it has become imperative to detect the target as soon as possible thereby requiring an increase in range. Further, the ability to simultaneously track a plurality of targets virtually eliminates the use of an antenna which requires the physical movement of a large mass. Therefore, phased array antennas which may be electronically steered at very high rates and which may simultaneously track a plurality of targets by producing time-shared radar beams are required.

In the prior art, phased array antennas have usually been designed in one of four geometrical configurations; linear, planar, cylindrical or spherical. The construction and design of cylindrical and spherical phased arrays is more complex and more expensive than the planar arrays. Further, curved phased arrays are less efficient than a planar array because they do not utilize all the radiating elements at specific angles of scan due to the curvature of the array.

The most common configuration used is the planar array which has a maximum gain $G(\theta)$ of a directive beam in a direction θ as measured from the outward normal of the array that is bounded by:

$$G(\theta) \leq (4\pi/\lambda^2) \cdot A \cos\theta$$

where A is the area of the antenna and λ is the operating wavelength. The maximum value of the scan angle θ is limited to less than 90° in principle and less than 70° in practice because of the difficulty in economically realizing efficient operation over extended scan ranges. For hemispheric coverage the use of a planar array has been summarized in an article entitled "Electronic Scanning Radar Systems" by Peter J. Kahrilas, which appeared in the Proceedings of the IEEE, November 1968, "In the case where hemispherical coverage is required the choice exists among the following: (1) four arrays, each covering approximately one-quarter of the hemisphere, or (2) three arrays, each covering approximately one-third of the hemisphere or (3) one array, mechanically rotating in azimuth and electronically scanning a pencil beam in elevation from 0° to 90°.

The single array can only be used for hemispherical coverage if it can meet the data rate and performance requirements, and if the target dynamics and target density are low enough to employ track-while-scan instead of continuous interpolative-null tracking."

Lens antennas are also well known in the radar antenna art. They have been used primarily for transforming a spherical wavefront produced by rays emerging from a smaller feed antenna into a flat or uniphase wavefront at the aperture of the lens. Metal-lens antennas which utilize the optical properties of radio waves have been the subject of an article by Winston E. Kock which appeared in the Proceedings of the IRE and Waves and Electrons, November 1946, pages 828–836.

Furthermore, radomes which are primarily used to protect antennas from severe weather conditions such as high winds, icing and extreme temperatures have been used in combination with antennas in the prior art to modify the polarization of radiated beams and to alter the phase configuration thereby compensating for radome phase distortion. In these applications the radomes may be considered to be functioning as lenses.

The subject invention discloses the use of a single planar phased array antenna in combination with a non-planar antenna lens which modifies the scan characteristics of the planar array to enable increased angular scan off broadside. One embodiment provides full hemispheric coverage using a single planar phased array antenna and a single passive lens.

SUMMARY OF THE INVENTION

The present invention is an antenna which employs a lens having generally a non-planar configuration positioned in the field of a conventional planar phased array antenna. The lens modifies the scanning properties of the planar phase array antenna thereby providing a combination antenna which generates beam patterns having characteristics, i.e., beamwidth and gain, that vary in accordance with the scan angle to conform to a given operational requirement. The lens may be a constrained type which includes a plurality of modules comprised of collector elements, phase shifter elements and radiator elements or may be a dielectric type. Electromagnetic energy radiated from the planar array portion of the antenna (referred to as the feed array) is directed to the lens and coupled therethrough to the radiating surface. The phasing of the feed array is such that when the electromagnetic energy is transmitted through the lens, the total electromagnetic energy radiated by the radiating surface of the lens combines to produce a collimated beam at a specific scan angle θ'. By changing the phasing of the feed array different collimated beams at different scan angles are generated. The lens imparts a phase delay to the incident electromagnetic energy whose value depends on the portion of the lens upon which the energy is incident. This causes the pattern characteristics of the collimated beams formed by the antenna to conform to the desired operational requirement.

When the phase gradients imposed by the lens are such that electromagnetic energy from the center of the feed array incident on the lens is refracted toward the broadside direction, the effect of the lens is to reduce the scan range of the planar phased array. However, to produce a collimated beam in the broadside direction, the planar array must be phased to form a diverging wave which has the effect of increasing the gain of the radiated beams in the vicinity of broadside to a value which is greater than that obtainable with a planar array of comparable size and number of elements in the feed array.

Further, when the phase gradients imposed by the lens are such that electromagnetic energy from the center of the feed array incident on the lens is refracted away from the broadside direction, the effect of the lens is to increase the scan range of the planar array. Then, to produce a collimated beam in the broadside direction, the planar array must be phased to form a converging wave which has the effect of reducing the gain of the radiated beams in the vicinity of broadside.

In the most general case, however, the phase gradients imposed by the lens are such that rays from the center of the feed array are refracted by varying amounts either toward broadside or away from broadside depending on which region of the lens they are incident. Then, to produce collimated beams, the feed array must be phased to form a predominately divergent wave for some directions of scan or a predominately convergent wave for other directions, resulting in corresponding increases or decreases of gain in those scan directions respectively.

Proper determination of the variation of phase delay in the lens causes the gain of the collimated beams to vary with scan angle in accordance with a prescribed operational requirement. Moreover, a direct consequence of achieving this high degree of conformity to the operational requirement is to reduce the size and number of elements in the feed array to an extent not possible with prior art antenna systems.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic representation of an antenna including a feed horn, a feed array and a lens illustrating the refractive action of the lens with respect to the feed array;

FIG. **2***a* is a typical ray diagram of a convergent beam from a phased array directed at a lens having a scan amplification factor greater than 1 which produces a beam parallel to broadside;

FIG. **2***b* is a typical ray diagram of a phased array convergent beam directed at a lens having a scan amplification factor greater than 1 which produces a beam at an angle of approximately 60° with respect to broadside;

FIG. **3***a* is a typical ray diagram of a divergent beam from a phased array directed at a lens having a scan amplification factor less than 1 which produces a beam parallel to broadside;

FIG. **3***b* is a typical ray diagram of a divergent beam from a phased array directed at a lens having a scan amplification factor less than 1 which produces a beam at an angle of approximately 10° with respect to broadside;

FIG. **4** is a graph of the relative aperture gain versus scan angle of a circular arc cylindrical lens;

FIG. **5** is a graph of gain versus scan angle from zenith for a three-dimensional wide angle scanning array;

FIG. **6** is a graph of antenna diffraction patterns of a circular cylindrical lens having a scan amplification factor of 1.5 for beam pointing directions of 0°, 30°, 60° and 90° with respect to broadside;

FIG. **7** is a schematic diagram of a lens in a combined phased array antenna and lens in which the lens includes dipoles;

FIG. **8** is a schematic diagram of a lens in a combined phased array and lens in which the lens includes circular waveguide elements;

FIG. **9** is a diagram of a hyperbolic nose cone dielectric lens and feed array;

FIGS. **10***a–j* are graphs of radiation patterns computed for a hyperbolic nose cone lens having a 5.5° cone half-angle;

FIG. **10***a* shows the pattern for 0° scan angle with −4.88 dB edge taper feed array illumination;

FIG. **10***b* shows the pattern for 0° scan angle from a uniformly illuminated feed array;

FIG. **10***c* shows the pattern for 30° scan angle from −4.88 dB edge taper feed array illumination;

FIG. **10***d* shows the pattern for 30° scan angle from a uniformly illuminated feed array;

FIG. **10***e* shows the pattern for 60° scan angle from −4.88 dB edge taper feed array illumination;

FIG. **10***f* shows the pattern for 60° scan angle from a uniformly illuminated feed array;

FIG. **10***g* shows the pattern for 90° scan angle from −4.88 dB edge taper feed array illumination;

FIG. **10***h* shows the pattern for 90° scan angle from a uniformly illuminated feed array;

FIG. **10***i* shows the pattern for 120° scan angle from −4.88 dB edge taper feed array illumination;

FIG. **10***j* shows the pattern for 120° scan angle from a uniformly illuminated feed array;

FIG. **11** is a cross-section of a spherical lens and a feed array radiating a convergent beam in a first direction and a divergent beam in a second direction;

FIG. **12** is a schematic representation of an antenna comprising a feed horn, a feed array and a lens in which the lens includes variable phase shifter elements.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** shows a typical embodiment of a phased array lens antenna **10** which includes a lens **11** which is substantially hemispherical in shape and has a plurality of collector elements **12** coupled through phase delays **13** to corresponding radiator elements **14.** Positioned in the near field of the lens **11** is a feed array **15** which includes collector elements **16** coupled through phase shifter elements **17** to radiator elements **20.** A feed horn **21** illuminates the collector elements **16** of the feed array **15** with electromagnetic energy received at the input to the feed horn **21.** The feed array **15** is of sufficient size and proximity to the lens **11** to illuminate it with a "search light" effect, i.e., the lens **11** is sufficiently in the near field of the feed array **15** to prevent a highly diffracted radiated beam pattern from forming.

While the phase delays **13** in the lens **11** may be variable, in order to simplify the explanation of the invention, they will be considered to be fixed phase delays and the phase shifters **17** in the feed array **15** are electronically controlled phase shifters which vary the direction of the radiated beam from the feed array toward the inner surface of the lens **11.** The maximum aperture gain of the antenna comprising the lens and feed array in any given direction is given by $G = (4\pi/\lambda^2)\ A_L\ (\theta)$ where $A_L\ (\theta)$ is the area of the lens **11** projected in the given direction.

Assuming the delays **13** are fixed, it is necessary to determine the variations in the values of the fixed phase delays **13.** Consider as shown in FIG. **1**, a ray **22** emanating from the midpoint of the feed array **15** at an angle θ with respect to the normal, N, of the plane, X—X, of the feed array **15.** The refractive action of the lens **11** is considered as occurring at a fictitious surface

23 as shown in FIG. 1 and located midway between the inner and outer surfaces of the lens **11**. The ray **22** is incident on the surface **23** at a point **24** and is refracted by the lens to an angle θ'. For the given geometry, this refraction uniquely defines a gradient of phase, tangential to the surface **23**, at the point **24**. By varying θ so that the ray **22** is incident upon the lens **11** at positions corresponding to each of the plurality of collector elements **12**, the phase gradient at every point corresponding to the fixed delays **13** on the surface **23** may be defined and thereby the relative values of the adjacent fixed delays **13** can also be defined. The ratio of θ' to θ is called the scan amplification factor, K.

For a spherical lens **11** of radius R and a constant scan amplification factor K, the values of the fixed phase delays **13** in the lens **11** may be determined as functions of θ as given in terms of wavelengths by: delay $= (R/K - 1) [1 - \cos (\theta' - \theta)]$.

When the values of the fixed delays **13** in the lens **11** have been established in the foregoing manner, the phasing of the feed array to obtain a well collimated beam scanned in a direction θ' must be determined. This is done by considering a plane wave incident on the outer surface of the lens **11** from the direction θ' and computing the field as it penetrates the lens **11** and irradiates the planar feed array **15**. The required phasing of the feed array **15** is then that of the complex conjugate of this field.

In many practical applications of this invention, the computation for determining the required phasing of the feed array **15** may be simply and validly performed by geometrical optic techniques. The cross-section spherical lens **11** having a value of K greater than 1 is shown in FIGS. 2*a* and 2*b* in combination with a feed array **15** that provides a converging beam as indicated by the plurality of rays **22***a–e*.

In FIG. 2*a*, the rays are directed toward the inner surface of the lens **11** and exit from the outer surface of the lens **22** as a directive beam. In FIG. 2*b*, the beam, as represented by the plurality of rays **11***a–e*, is directed toward the inner surface of the lens **11** to the right of the normal, N, and exits from the outer surface of the lens **11** as a directive beam. It will be noted that the angles θ_a–θ_e have been increased with respect to the normal, N, to angles θ_a'–θ_e' which are all equal forming the directive beam which exits from the lens **11**. The refraction is different for each ray **22***a–e* because the angles θ_a–θ_e are not equal but the angles θ_a'–θ_e' are equal.

The image of the aperture of the feed array **15** as projected through the lens **11** for scan directions near the normal, N, is less than that of the feed array **15** without the lens **11**. Therefore, while an antenna comprised of a feed array **15** and a lens **11** having a scan amplification factor, K, greater than 1, will increase the scan range of the planar feed array **15** there is a reduction of gain for beams near broadside.

A spherical lens **11** having values of K less than 1 is shown in FIGS. 3*a* and 3*b* in combination with a feed array **15** that provides a diverging beam as indicated by the plurality of rays **22***f–j*. In FIG. 3*a*, the rays are directed toward the inner surface of the lens **11** and exit from the outer surface of the lens **11** as a directive beam. In FIG. 3*b*, the beam, as represented by the plurality of rays **22***f–j*, is directed toward the inner surface of the lens **11** subtantially to the right of the normal, N, and exits from the outer surface of the lens as a directive beam. It will be noted that the angles θ_f–θ_j have been decreased with respect to the normal, N, to angles θ_f'–θ_j' which are all equal and form the directive beam which exits from the lens **11**. While this has the effect of reducing the range of scan of the antenna, it provides an increase in the gain of the beams in the vicinity of broadside beyond that which could be achieved with a planar feed array comparable in size and number of elements to that in the feed array **15**.

FIG. 4 is a graph of scan angle versus relative aperture gain in dB for a linear feed array **15** and a circular arc cylindrical lens **11**. The ratio a/ρ defines the ratio of the feed array size to the radius of the lens in which a is the length of the feed array and ρ is the radius of the lens. The $K = 1$ plot represents the case where the lens does not impart a phase variation to the incident energy and hence represents the feed array alone for all values of a/ρ. The two plots of antennas comprised of a feed array and lens in which the scan amplification factor, $K = 0.5$ shows an increase in gain with an attendant reduction in the angle of scan. The two plots of an antenna having a scan amplification factor, $K = 1.5$ and the two plots of an antenna having scan amplification factor, $K = 2.0$ show a reduction in the relative aperture gain with an attendant increase in the range of scan.

FIG. **5** is a graph of scan angle versus relative gain in dB for a planar feed array **15** and spherical lenses **11** having scan amplification factors $K = 1.0$, 1.5, 1.75 and 2.0. These plots show the envelope of the peak gain of the antenna as the beam is scanned from the normal, N, relative to the broadside gain of a planar array having a size comparable to the feed array **15**.

The plots in FIGS. **4** and **5** graphically illustrate that for applications requiring a scan range of less than 45° from the normal, the effect of the invention is to reduce the size of the array **15** and therefore reduce the number of phase shifters **17** needed to realize a given gain. Further, for applications requiring an extremely wide scan coverage, i.e., greater than 70° with respect to the normal, the effect of the invention is to provide a mechanism for efficiently generating the desired angular coverage with a single planar array **15**.

FIG. **6** shows the computed diffraction patterns of an antenna employing a circular cylindrical lens having a scan amplification factor, $K = 1.5$ with the collimated beam directed at 0°, 30°, 60°, and 90°, and the sidelobes maintained at a maximum of -28 dB relative to the respective beam peak.

A more general approach to the use of the scan amplification factor, K, for selecting the values of the fixed delays **13** in the lens **11** is based on the envelope of the peak gain of the scanned beams which is the average power pattern of the elements in the feed array **15**, as measured in the far field in the presence of the lens **11**. The average power pattern of the element in the feed array **15** would be the gain versus scan variation of the feed array alone. The lens **11** acts to alter the element pattern of the feed array **15** and hence the gain-versus-scan variation of the antenna **10**. A method for tailoring the element pattern of the central element of the feed array **15** is based on a technique well known in the art of designing shaped reflectors. For a complete discussion of this technique, reference is made to Microwave Antenna Theory and Design, Samuel Silver, McGraw-Hill, New York, 1949, pages 494–500. This technique defines the relationship between the angles θ and θ' using geometrical optics so as to provide the proper flow of energy required to synthesize the desired element pattern shape. In a symmetrical system, the θ–θ' relationship is expressed by the integral equation:

$$\int_0^{\theta'} G(\theta)\ \sin\ \theta d\theta=\int_0^{\theta} G_e(\theta)\ \sin\ \theta d\theta$$

where $G_e(\theta)$ is the element gain pattern of the feed array **15** without the lens and $G(\theta)$ is the desired element gain pattern of the feed array **15** with the lens **11** or the desired normalized gain-versus-scan variation of the antenna **10.** When the relationship between θ and θ' is so defined, the values of the fixed delays **13** are determined in a manner identical to that described in the technique employing the scan amplification factor.

This approach for selecting the values of the phase delays **13** in the lens **11** enables the design of lens-array systems which satisfy more sophisticated requirements than possible using the constant scan amplification approach. For instance, an application may dictate that a constant signal be maintained from a ground based system at a specific altitude over a given range. This requires a broad beam with low gain directly overhead and narrow beam with high gain at wide scan angles. FIG. **11** shows a phased array fed spherical lens applicable to this requirement. The phase delays in the lens are determined using the technique described in the above paragraph. Thus, for a scan direction directly overhead the feed array **15** is phased to provide a highly convergent beam of electromagnetic energy. As illustrated in FIG. **11**, this results in only a small section of the lens being illuminated resulting in a broad beam with low directive gain. For the scan direction requiring the narrowest beam with the highest gain, the feed array **15** is phased to form a divergent beam of electromagnetic energy. As illustrated in FIG. **11**, this results in a large portion of the lens being illuminated resulting in a narrow beam with a high directive gain. For scan angles in between these two, the lens phase delays necessitate the phasing of the feed array be such as to illuminate a portion of the lens of sufficient size to satisfy the beamwidth and gain requirements in the specific direction of scan.

In operation, electromagnetic energy from a feed horn **21** as shown in FIG. **1** is radiated toward the collector elements in the feed array **15** and coupled through electronically controlled phase shifters **17** to the radiator elements **20** on the feed array. The electronically controlled phase shifter elements **17** determine the direction of the radiated energy from the radiating elements **20** toward the inner surface of the lens **11.** The phasing of the radiated energy from the feed array **15** determines which of the plurality of collector elements **12** on the lens **11** receive the radiated energy from the feed array **15.** These collector elements **12** couple the received energy through the fixed phase delays **13** to the radiator elements **14** on the lens **11** and provide a directive beam of electromagnetic energy from the antenna **10.** The characteristics of the radiated beam from the antenna **10** are determined by the lens phase shift, the length of the feed array **15** and the configuration of the lens **11.**

The lens **11** may be comprised of a variety of elements in accordance with techniques that are well known in the lens and antenna arts. As shown in FIG. **7**, one such embodiment includes dipole collector elements **30** coupled through flexible cables **31** which function as fixed phase delays mounted within the lens structure **11** and coupled to dipole radiator elements **32.** The length L of the flexible cable is varied from element to element so as to provide the proper relative phase variation between the transmission paths in the lens **11.** An alternate configuration for the lens **11** is shown in FIG. **8** wherein the collector elements **33** and the radiator elements **35** are open ended circular waveguides with appropriate matching structures **34** coupled therebetween. These elements are dielectrically loaded to provide a size sufficiently small for arrangement in a lattice capable of being matched over a wide range of incident angles. The matching structure **34** is a circular waveguide section loaded with two different dielectric materials of lengths L_1 and L_2. The sum of the physical lengths L_1 and L_2 is a constant for all transmission paths within the lens **11** while the ratio of lengths L_1 to L_2 determines the relative phase delay for a given element.

Although the element in the lens **11** may be arranged in a variety of lattice configurations, the inter-element spacing should be no greater than that dictated by the grating lobe condition:

$$\lambda min/1+\sin\alpha$$

where λ_{min} is the minimum operating wavelength of the antenna and α is the maximum angle of incidence on the inner surface of the lens **11** or transmission from the outer surface of the lens **11.**

The subject invention may also be employed in an airborne system in which the lens **51** is a dielectric lens formed in a streamline configuration to conform to the nose profile of a high speed aircraft as shown in FIG. **9.** In one embodiment of the invention, a hyperbolic nose cone lens is fabricated of titanium dioxide and the geometry of the lens provides a wide range of scan in excess of ±120° with respect to the apex of the lens at a transmission frequency of 16 GHz. Since the nose cone is a lens of a homogeneous medium and not a constrained lens, i.e., a lens with a plurality of transmission paths as provided by the collectors, fixed phase delays and radiator elements of the lenses **11,** the phase delay in the dielectric lens **51** is realized by means of a change in the refractive index of the lens material or by varying the thickness of the lens material between the base and the apex of the nose cone. The hyperbolic nose cone dielectric lens **51** shown in FIG. **9** has an asymptotic 5.5° cone half-angle, a scan amplification factor $K = 1.7$ and a feed array length of 40 λ.

FIG. **10***a* shows a radiation pattern for this lens at a scan angle of 0° and a −4.88 dB edge taper feed array illumination and FIG. **10***b* shows the radiation pattern for the same lens at 0° scan angle with a uniformly illuminated feed array. Similar results were obtained for the computed radiation patterns for the same nose cone under the same operating conditions at 30° as shown in FIGS. **10***c* and **10***d;* at 60° as shown in FIGS. **10***e* and **10***f* and at 90° as shown in FIGS. **10***g* and **10***h.*

Although the computed radiation patterns for the hyperbolic nose cone for 120° of scan angle showed a decrease in the directivity of the radiated beam due to increased width in the main lobe, it still provided sharp discrimination with respect to the sidelobes.

The lenses and arrays as disclosed are shown in one plane; however, it will be readily appreciated that the spherical and hemispherical lenses with scan amplification factors greater than 1 provide hemispherical coverage, i.e., angles of scan greater than ±90° from the broadside direction for all azimuth scan angles in the same embodiment. Therefore, rather than requiring three or four arrays to provide hemispheric coverage, the subject invention requires a single planar feed array in combination with a lens having an effective scan amplification factor greater than 1. In addition, it does not require mechanical rotation of the elements and thereby provides scanning at a maximum rate.

It will also be appreciated by those skilled in the art that the physical structure required to implement the invention described herein may be fabricated of lightweight material and components known in the art which may be quickly assembled and disassembled for portability.

While the above embodiments employ feed arrays which incorporate electronic phase controls only, the disclosed invention is equally suitable to more sophisticated planar feed array configurations such as those which incorporate devices for electronically controlling the amplitude and the polarization of the feed array excitation to enhance the performance of the system.

Further as mentioned previously, to simplify the explanation of the invention, a passive lens has been cited in the foregoing embodiments. The lens however may be constructed in such a manner as to permit variation of the phase gradient in the lens by either electronic or manual means. This allows the scanning properties of the antenna to be altered on a time scale consistent with the time required to effect the lens phase gradient variation. Used in conjunction with a multi-function radar, for example, such a design facilitates optimization of each of the operating modes of the radar system. FIG. **12** shows a typical embodiment of a phased array lens antenna **10'** substantially similar to that shown in FIG. **1** except that the phase delays **13** of FIG. **1** are replaced by variable phase shifter elements **13'**. Moreover, when electronic phase shifters **13'** are used to produce the phase delay in the lens **11**, the variation of gain with scan angle can be designed such as to approach the maximum aperture gain of the antenna as previously defined. Then, the gain, averaged over all scan angles, will generally exceed that realizable by the equivalent antenna using passive phase delay in the lens **11**.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation and that changes may be made within the purview of the appended claims without departing from the true scope and spirit of the invention in its broader aspects.

We claim:

1. An electronic scanning antenna system comprising a source of electromagnetic energy,

array means including elements, said array means being coupled to said source of electromagnetic energy for producing a first beam of electromagnetic energy having a non-planar phase and controllable focal properties, and

lens means responsive to said first beam of electromagnetic energy having a non-planar phase and controllable focal properties which implement a phase gradient for producing a directive second beam of electromagnetic energy having a plane wavefront, a variable range of scan and an attendant variable gain.

2. An electronic scanning antenna system as described in claim **1** in which said source of electromagnetic energy includes a radiating feed horn.

3. An electronic scanning antenna system as described in claim **1** in which said array means coupled to said source of electromagnetic energy includes means for producing a converging first beam of electromagnetic energy having a pre-determined non-planar phase, said array means being capable of producing a first beam of electromagnetic energy at a specific gain over a limited range of scan.

4. An electronic scanning antenna system as described in claim **3** in which said lens means includes means for varying said phase gradient whereby said second beam of electromagnetic energy has an increased range of scan over said limited range of scan with an attendant minimum reduction of gain from said specific gain.

5. An electronic scanning antenna system as described in claim **3** in which said lens means has a fixed phase gradient in all directions for transmitting a directive second beam of electromagnetic energy having a plane wavefront and an increased range of scan over said limited range of scan with an attendant minimum reduction in gain from said specific gain of said array means.

6. An electronic scanning antenna system as described in claim **1** in which said array means includes means for producing a diverging first beam of electromagnetic energy having a pre-determined non-planar phase, said array means being capable of producing a first beam of electromagnetic energy at a specific gain over a limited scan range.

7. An electronic scanning antenna system as described in claim **6** in which said lens means includes means for varying said phase gradient to produce a second beam of electromagnetic energy having a plane wavefront and a reduced range of scan with respect to said limited range of scan and an attendant increase in gain over said specific gain.

8. An electronic scanning antenna system as described in claim **6** in which said lens means includes a fixed phase gradient for transmitting a directive second beam of electromagnetic energy having a plane wavefront and a reduced range of scan with respect to said limited range of scan and an increase in gain over said specific gain of said array means.

9. An electronic scanning antenna system as described in claim **1** in which

said array means further includes means for providing a converging first beam in a first direction and means for providing a diverging first beam in a second direction, and

said lens means includes means for varying said phase gradient for producing, in response to said converging first beam, a second beam of electromagnetic energy having a plane wavefront directed in said first direction within a first prescribed range of scan with an attendant reduction in gain from said specific gain and means for varying said phase gradient for producing, in response to said diverging first beam, a second beam of electromagnetic energy having a plane wavefront directed in said second direction within a prescribed range of scan with an attendant increase in gain over said specific gain thereby providing an antenna system having a minimum number of elements.

10. An electronic scanning antenna system as described in claim **1** in which said array means includes

collector elements for receiving said electromagnetic energy provided by said source of electromagnetic energy,

electronically controlled phase shifter elements coupled to said collector elements and

radiator elements coupled to said electronically controlled phase shifter elements.

11. An electronic scanning antenna system as described in claim **1** in which said lens means includes collector elements for receiving said first beam of electromagnetic energy,

variable phase shifter elements coupled to said collector elements for implementing said phase gradient, and radiator elements coupled to said variable phase shifter elements for transmitting said directive second beam of electromagnetic energy.

12. An electronic scanning antenna system as described in claim **1** in which said lens means includes a lens having a non-planar shape.

13. An electronic scanning antenna system as described in claim **12** in which said lens has a spherical configuration.

14. An electronic scanning antenna system as described in claim **12** in which said lens means includes a lens having a cylindrical configuration.

15. An electronic scanning antenna system as described in claim **1** in which said lens means is portable.

16. An electronic scanning antenna system as described in claim **1** in which said lens means includes a lens of dielectric material having a variable thickness and non-planar shape whereby the focal properties of said lens are controlled in accordance with said variable thickness and non-planar shape.

17. An electronic scanning antenna system as described in claim **16** in which said lens has a geometrical shape which conforms to the nose profile of a high speed vehicle.

18. An electronic scanning antenna system as described in claim **16** in which said lens is fabricated of titanium dioxide.

19. An electronic scanning antenna system as described in claim **1** in which said lens means includes dipole collector elements for receiving said first beam of electromagnetic energy,

flexible cables of varying length coupled to said dipole collector elements, and

dipole radiator elements coupled to said flexible cables for transmitting said directive second beam of electromagnetic energy.

20. An electronic scanning antenna system as described in claim **1** in which said lens means includes open-ended collector elements for receiving said first beam of electromagnetic energy,

dielectrically loaded circular waveguides coupled to said collector elements for imparting different relative phase delays to said first beam, and

open-ended radiator elements coupled to said circular waveguides for transmitting said directive second beam having a plane wavefront.

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