343-754 CROSS REFERENCE SEARCH ROOM

April 5, 1955 J. S. JAFFE 2,705,753

DELAY REFLECTOR ANTENNA

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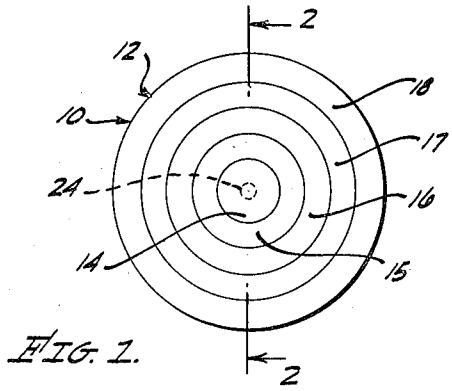


FIG. 1.

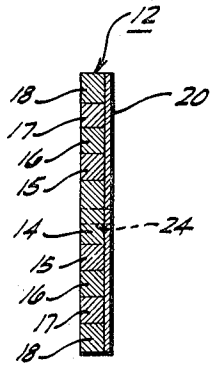


FIG. 2.

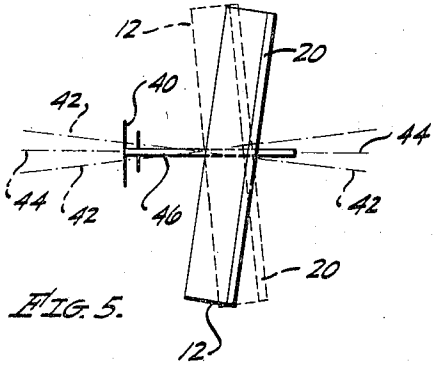
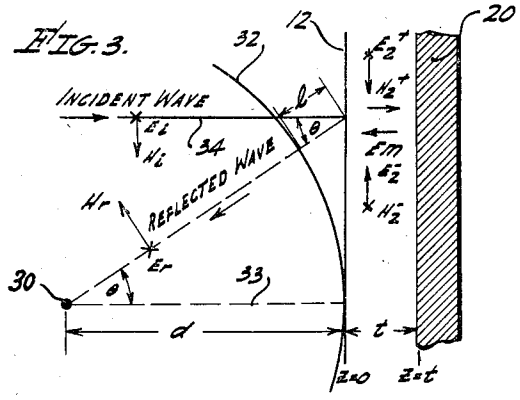


FIG. 5.

FIG. 3.



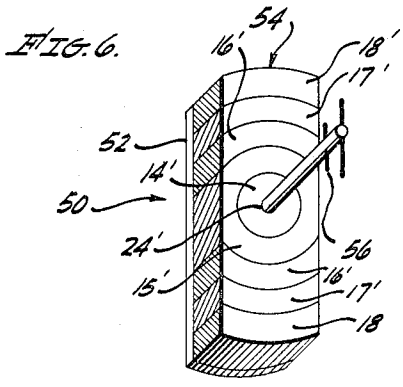


FIG. 6.

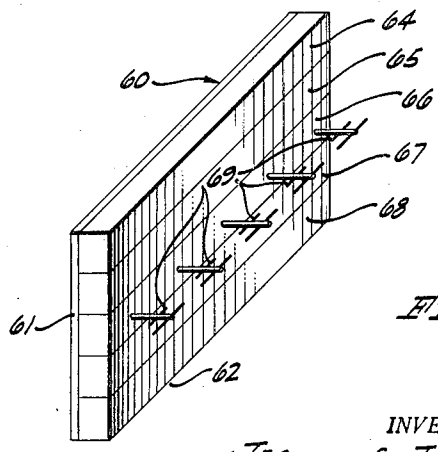


FIG. 7.

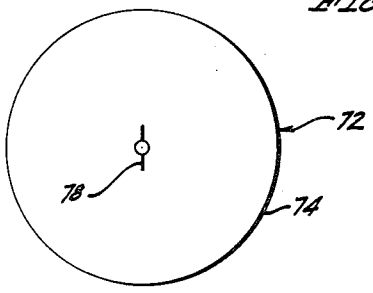
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DELAY REFLECTOR ANTENNA

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FIG. 8.



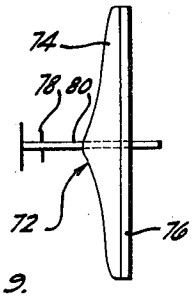


FIG. 9.

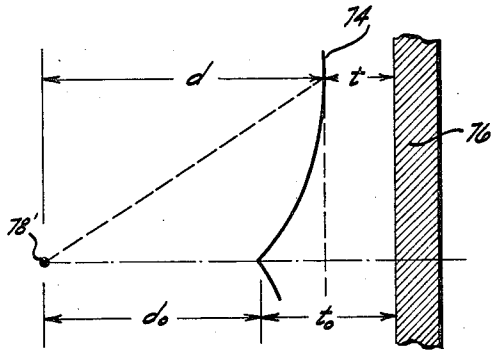


FIG. 10.

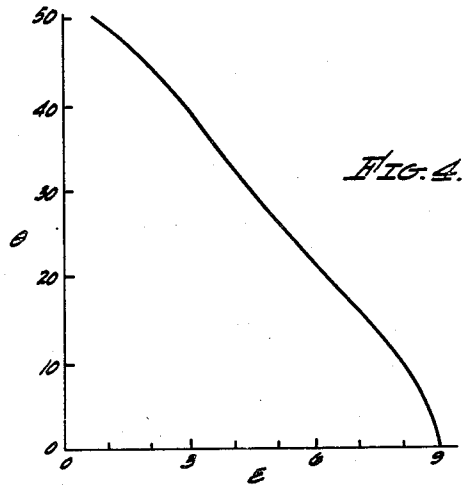


FIG. 4.

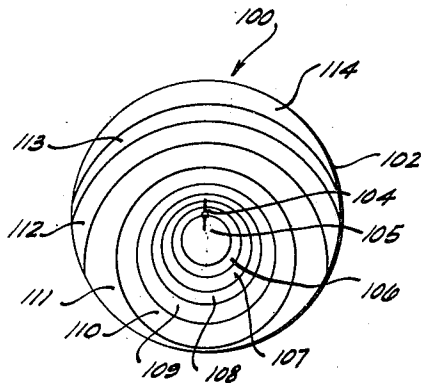


FIG. 12.

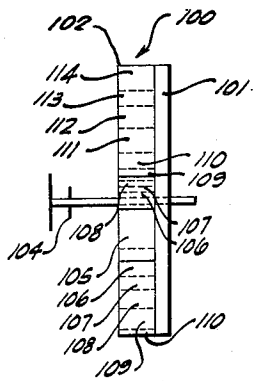


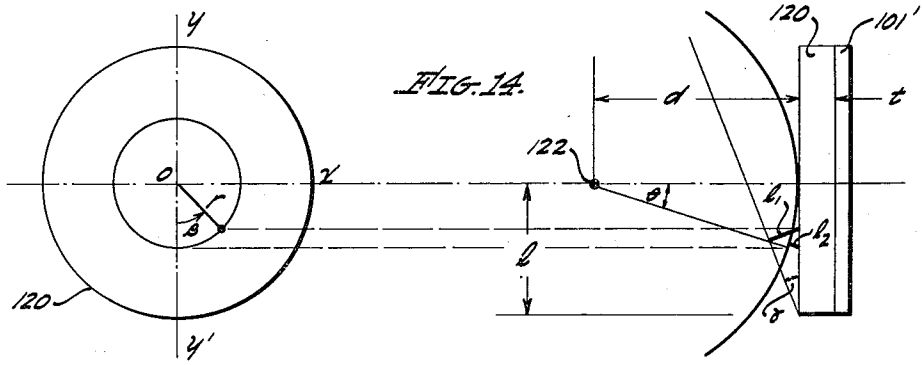
FIG. 13.

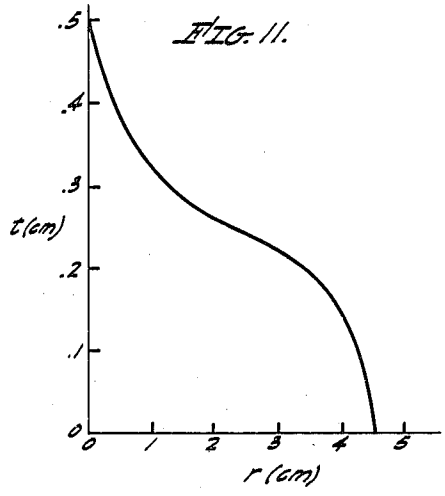
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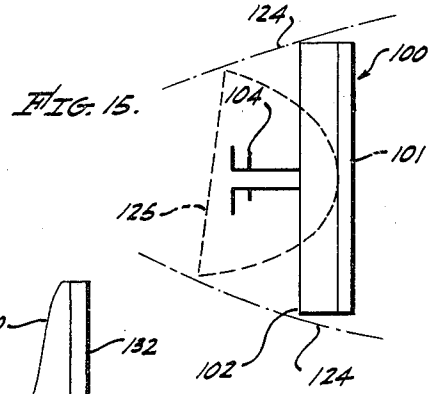
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DELAY REFLECTOR ANTENNA

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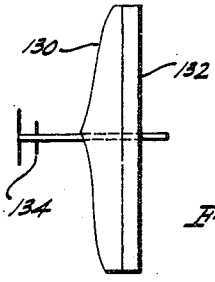


FIG. 16.

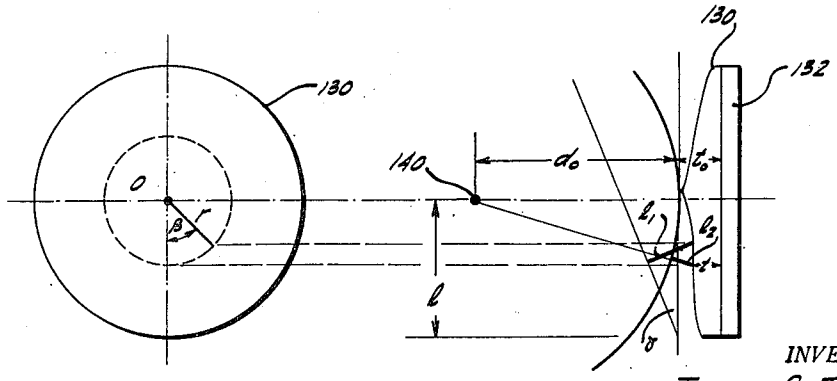


FIG. 17.

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2,705,753

DELAY REFLECTOR ANTENNA

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Application August 16, 1952, Serial No. 304,747

17 Claims. (Cl. 250—33.65)

This invention relates to antenna systems, and more particularly to reflectors for use in microwave antenna systems, such as radar transmitting or receiving antenna systems and microwave radio relay links.

A reflector, as commonly used in microwave application, is employed in conjunction with an illuminating source to establish a desired antenna pattern. The function of the reflector in a transmitting antenna system is to propagate, in a selected direction, energy directed to the reflector from the illuminating source, while in a receiving antenna system it functions to receive electromagnetic energy from a selected direction and to impress such energy upon the illuminating source, the latter acting as a collector or receiver of the energy.

One type of antenna reflector commonly used in microwave application is the parabolic reflector. In transmitting systems, or reciprocally for receiving systems, the parabolic reflector is provided with an illuminating source which directs the major portion of its energy toward the central part of the reflector. Since the energy emanates essentially from a point source, the phase front of the energy is substantially spherical in nature. Because of the contour of the parabolic reflector, the energy can be provided with a total phase delay so that points of equal phase of the reflected energy lie in a plane adjacent the aperture of the parabolic reflector, i. e., the reflected energy has a plane phase front, and the energy is propagated from the reflector with optimum directivity and a minimum of undesirable radiation. Because of the applicability of reciprocity principle to this arrangement, the same antenna arrangement can be used for receiving as well as transmitting radiant energy; therefore, it follows that electromagnetic waves having a plane phase front, incident upon the reflector of the above type, will be converted by the reflector into energy having a spherical phase front to be focused upon the radiator.

The meaning of some of the terms as they will be used in this specification will be as follows: the term "antenna system" will include an illuminating source, as well as, a reflector, and the term "illuminating source" will include any known illuminating source suitable for illuminating the reflector with radiant energy in a transmitting antenna system and for intercepting the collected and focused radiant energy received by the reflector in a receiving antenna system.

To date, parabolic reflectors have been of sufficient utility for certain purposes to warrant their use in spite of many difficulties such use presents. In the production of such reflectors, for instance, great care must be taken to insure that they are shaped properly, i. e., extremely close contour or profile tolerances must be maintained. In addition, in the mounting of parabolic reflectors, their shape presents many balancing problems which must be solved, and these problems are still more numerous when such reflectors are to be moved and spun to produce various scanning patterns.

Furthermore, as will be pointed out later in this specification, reflectors of the type disclosed here are more compact than parabolic reflectors, whereby aperture space available, as for instance in "streamlined" housings, can be used more fully to obtain greater antenna gain.

The disclosed invention includes antenna reflectors of simple design which have substantially all the advantages and eliminate many of the disadvantages of the prior art parabolic reflectors.

In one embodiment of the present invention, a flat disk of dielectric material of uniform thickness has a dielectric constant which varies from the center of the disk toward its rim. The disk is mounted on a metallic member, with one flat surface of the disk in registry with said member. An illuminating source is placed on the axis of the disk for illuminating the disk with electromagnetic energy waves. Such waves travel through the dielectric disk to the metallic member, where they are reflected back through the dielectric disk and radiated therefrom. The electrical path length for each wave depends upon the transmission characteristic of the dielectric material at the portion of the disk through which the wave travels; the transmission characteristic in turn depends upon the dielectric constant at the portion of the disk through which the wave travels. The dielectric constant of the disk varies so as to provide transmission characteristics which produce constant phase delays of the illuminating waves and effect a maximum obtainable directivity of the emerging waves, i. e., the electrical path lengths of all the waves are constant because of variable delay furnished by the dielectric, and the energy emerges from the disk with a uniform phase front across the aperture of the disk. When this combination is used to receive electromagnetic waves, the received waves pass through the disk to the metallic member, where they are reflected back through the disk; the variation in the dielectric constant of the disk, i. e., the variation of the transmission characteristics of the disk, causes the reflected energy to be focused at the illuminating source. There is thus provided a delay lens antenna reflector of uniform thickness which functions in the manner of a parabolic reflector and which can be mounted and balanced with relative ease.

According to another version of the invention, the dielectric lens has a constant dielectric coefficient but varying thickness for obtaining optimum directivity.

Additional versions of the invention are disclosed which include disk reflectors for obtaining conical scanning and also reflectors for obtaining directive beams of the type normally obtainable with parabolic cylinders and truncated paraboloid reflectors.

The advantages and specific applications of all the above versions will be pointed out below in connection with more detailed descriptions thereof.

Accordingly, it is an object of this invention to provide an antenna including an illuminating source and a novel reflector for establishing a highly directive field pattern.

It is also an object of this invention to provide an antenna reflector including a dielectric element with at least one flat surface, and a metallic backing on said one flat surface, wherein the dielectric element has transmission characteristics in terms of delay time for energy radiations passing through said dielectric element toward said one flat surface and reflected back through said dielectric element to convert a plane phase front of energy incident upon said dielectric element into a substantially spherical phase front for focusing such energy at least at one predetermined point located at a focus of the dielectric element.

It is another object of this invention to provide a delay lens antenna reflector including an element of dielectric material having at least one flat surface, a metallic backing on said one flat surface, said material including a plurality of zones each having a thickness and dielectric constant effective to convert a spherical phase front of electromagnetic energy incident upon said dielectric element into a plane phase front of the energy emerging from said dielectric element.

It is an additional object of this invention to provide a delay lens antenna reflector in which a circular electromagnetic wave lens element of dielectric material is provided with means on one flat surface for reflecting electromagnetic waves, wherein said dielectric material includes a plurality of concentric zones having different dielectric constants, in which electromagnetic waves from an illuminating source spaced from and adjacent to said dielectric element are directed through the dielectric element to said one flat surface and reflected back through the dielectric element so as to have a uniform phase front across the aperture of said dielectric element.

It is still another object of this invention to provide a plane delay lens antenna reflector including a flat, symmetrical element of dielectric material of uniform thickness with a metallic backing, the element having a variable

dielectric constant, and the combination acting as a directive reflector for transmitting and receiving electromagnetic waves.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of examples. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention. In the drawings:

Figure 1 is a front elevation of a disk shaped antenna reflector of uniform thickness having symmetrical dielectric zones;

Figure 2 is a side view, in section, along line **2—2** of the reflector shown in Figure 1;

Figure 3 is an enlarged side elevation of a portion of the reflector of Figure 1, to illustrate the effect thereof on electromagnetic waves received thereby;

Figure 4 is a characteristic curve showing certain relationships for a reflector of the type shown in Figures 1 and 2;

Figure 5 is a side elevation of a disk reflector of the type shown in Figure 1 in a preferred arrangement with an antenna feed to provide a conical scanning antenna system;

Figure 6 is a perspective view of an antenna reflector, showing a reflector of uniform thickness in the form of a symmetrical frustrum of a disk;

Figure 7 is a perspective view of a plane rectangular antenna reflector of uniform thickness;

Figure 8 is a front elevation of a circular antenna reflector of variable thickness;

Figure 9 is a side elevation view of the reflector shown in Figure 8;

Figure 10 is an enlarged sectional view of a portion of the reflector shown in Figure 9 for the purposes of analysis;

Figure 11 is a characteristic curve showing certain relationships of the type of reflector shown in Figures 8–10;

Figure 12 is a front elevation of a disk-shaped antenna reflector of uniform thickness having eccentric circular sections or dielectric zones;

Figure 13 is a side elevation of the reflector shown in Figure 12;

Figure 14 is an illustration of a disk shaped reflector for the purposes of analysis in determining the shape of the sections of the reflector of Figures 12 and 13;

Figure 15 is an illustration comparing a parabolic reflector and the reflector of Figures 12 and 13 as employed for conical scanning;

Figure 16 is a side elevation of a reflector, of the type shown in Figures 8–10, arranged in a predetermined manner for conical scanning; and

Figure 17 is an illustration of a reflector of the type shown in Figure 16 for the purposes of analysis.

Referring to the drawings, in which like reference characters indicate like parts throughout, and referring more particularly to Figures 1 and 2, an antenna reflector **10** employs an electromagnetic wave lens comprising a dielectric element or disk **12** of uniform thickness. The dielectric disk **12** includes a plurality of concentric dielectric zones **14**, **15**, **16**, **17**, and **18** of equal thickness which, as will be explained more clearly hereafter, have respective dielectric constants ϵ_{14}, ϵ_{15}, ϵ_{16}, ϵ_{17}, and ϵ_{18} that vary in discrete steps from the center of the dielectric disk **12** towards its rim.

Ideally, the dielectric disk **12** would be a single disk of dielectric material of uniform thickness in which the dielectric constant is a function of the radial distance from the axis of the reflector. In the absence of dielectric elements of uniform thickness which exhibit such characteristics, a practical arrangement would be a dielectric disk in which the concentric dielectric zones **14**, **15**, **16**, **17**, and **18** are made of suitable dielectric materials of equal thicknesses but having different dielectric constants. The above can be obtained, for example, by rings made of combinations of polystyrene and titanium dioxide in different proportions. Where rings of different dielectric materials are employed in the manner of the concentric zone portions **14—18** shown in Figure 1, they may be joined into a unitary structure by means of a suitable bonding material, such as polystyrene cement, which will not affect the transmission properties of the reflector; such bonding material may be applied between the registering peripheral surfaces of the adjacent rings.

A metallic layer or reflecting surface is provided on one flat surface of the dielectric disk **12** for reflecting radiant energy that passes through the dielectric disk toward such flat surface. Such metallic layer may be provided by a metallic disk **20**, as shown in Figure 2, or by a highly conductive metallic coating or backing applied to the dielectric disk **12**. Where the dielectric disk **12** is mounted on a metallic disk, the two disks may be secured by means of a suitable bonding material, such as polystyrene cement.

Figure 3 illustrates the geometry of wave propagation through a portion of the dielectric disk **12**. If an incident wave enters the dielectric disk **12** substantially normal to the metallic reflecting surface or metallic disk **20**, the dielectric constant of the zone through which the wave enters the dielectric disk **12** has a transmission characteristic in terms of delay time, or phase delay, for focusing the wave **34** at a predetermined focal point **30** on the axis **33** of the dielectric disk **12**, and, therefore, a parallel beam of electromagnetic waves incident upon the dielectric disk **12** will be provided with a constant phase delay and focused at the focal point **30** upon emerging from the dielectric disk **12**, that is, the dielectric disk **12** provides equal electrical path lengths for incident electromagnetic waves having a uniform or plane phase front so that such plane phase front is converted into a spherical phase front to cause focusing of such waves at a common point. A suitable illuminating source may be located at the focal point **30** to collect the focused energy.

Figure 3 illustrates conditions for determining the dielectric constant at any point on the dielectric disk **12** to effect the focusing of an electromagnetic wave incident upon the dielectric disk at such point. An analysis of such conditions that is based upon electromagnetic theory results in the derivation of the following formula:

$$\cos\theta=\frac{kd}{K+kd+2\tan^{-1}[\sqrt{\epsilon}\cot(\sqrt{\epsilon}kt)]} \qquad (1)$$

where

d=a constant representing the distance from the center of the dielectric disk **12** to the focal point **30**

k=a constant for electromagnetic waves of a predetermined wavelength

t=a constant representing the thickness of the dielectric disk **12**

θ=a constant for the point of incidence of an electromagnetic wave to represent the angle at which a reflected wave, upon emerging from the dielectric disk, must be deflected to be focused at the focal point **30**

K=a constant representing the total phase shift required to obtain an optimum field intensity pattern.

Thus, for any point on the dielectric disk **12**, the value of the dielectric constant ϵ required to effect the desired focusing of an electromagnetic wave in the manner above explained is easily determined by solving the above Equation 1 for the value of ϵ which, with the values of the constants above explained, will satisfy the equation. Since the value of the dielectric constant determined for one point at a certain radial distance from the center of the dielectric disk **12**; will be the same for all points at the same radial distance from the center, each value of the dielectric constant ϵ which satisfies the above equation represents the value of the dielectric constant of a zone that is concentric with the axis of the dielectric disk **12**.

It is assumed that, at any point along the dielectric surface upon which a plane wave impinges, the dielectric material of thickness t and dielectric constant ϵ has an infinite radial extent, and is provided with a "perfect" electromagnetic wave reflecting boundary at the surface thereof opposite the surface of incidence of such wave; the total tangential electric field on the walls of a perfect conductor is zero. It will be clear from the following mathematical treatment that such assumption aids materially in deriving equations for determining the dielectric constant required at each point of a disk of uniform thickness for effecting desired phase delay and focusing of a plane wave impinging thereon. It will also be noted that multiple reflections of the wave within the dielectric ma-

terial are accounted for by applying proper boundary conditions.

Referring to Figure 3, the condition to be fulfilled is that the total phase shift be a constant, K. Thus:

$$K=\frac{2\pi}{\lambda}l+\phi \tag{2}$$

or

$$K=\frac{2\pi}{\lambda}\left[\frac{d}{\cos\theta}-d\right]+\phi \tag{3}$$

where

K=a constant, as above described
λ=free space wave length
d=a constant, as above described
ϕ=a phase shift in dielectric medium
t=a constant, as above described

As shown:

E_i=incident electric field
H_i=incident magnetic field
E_r=reflected electric field
H_r=reflected magnetic field
E_m=electric field in dielectric medium
H_m=magnetic field in dielectric medium

Letting:

$$E_i=E_0e^{ikZ} \tag{4}$$

$$H_i=\frac{k}{\omega\mu}E_i \tag{5}$$

$$E_r=E_1e^{-ikZ} \tag{6}$$

$$H_r=\frac{-k}{\omega\mu}E_r \tag{7}$$

$$E_m=E_2^+e^{ik_mZ}+E_2^-e^{-ik_mZ} \tag{8}$$

$$H_m=\frac{k_n}{\omega\mu_m}(E_2^+e^{ik_mZ}-E_2^-e^{-ik_mZ}) \tag{9}$$

where

$$k=\frac{2\pi}{\lambda}$$

$\omega=2\pi f$
μ=permeability (μ=1 for mediums considered here)
f=radio frequency (cycles/sec.)

Applying the boundary conditions, and assuming the fields to be continuous across the boundary:

(1) At $Z=t$, $E_m=0$

or

$$E_2^+e^{ik_2t}+E_2^-e^{-ik_2t}=0 \tag{10}$$

(2) At $Z=0$

$$E_i+E_r=E_m \tag{11}$$

or

$$E_0+E_1=E_2^++E_2^- \tag{12}$$

$$H_i+H_r=H_m \tag{13}$$

or

$$\frac{k_1}{\omega\mu_1}(E_0-E_1)=\frac{k_2}{\omega\mu_2}(E_2^+-E_2^-) \tag{14}$$

and

$$E_0-E_1=\frac{k_2}{k_1}(E_2^+-E_2^-) \tag{15}$$

Since

$$k_1=k=\frac{2\pi}{\lambda} \text{ and } \lambda_2=\frac{\lambda}{\sqrt{\epsilon}}$$

$$\frac{k_2}{k_1}=\frac{\lambda_1}{\lambda_2}=\frac{\lambda}{\lambda/\sqrt{\epsilon}}=\sqrt{\epsilon} \tag{16}$$

$$E_0-E_1=\sqrt{\epsilon}(E_2^+-E_2^-) \tag{17}$$

and

$$E_2^-=-E_2^+e^{2ik_2t} \tag{18}$$

By algebraic manipulation

$$\frac{E_1}{E_0}=\frac{1-j\sqrt{\epsilon}\cot(k_2t)}{1+j\sqrt{\epsilon}\cot(k_2t)} \tag{19}$$

ϕ is the phase difference between E_1 and E_0.

$$\phi=\tan^{-1}[-\sqrt{\epsilon}\cot(k_2t)]-\tan^{-1}[+\sqrt{\epsilon}\cot(k_2t)] \tag{20}$$

Since $k_2=\sqrt{\epsilon}k$,

$$\phi=-2\tan^{-1}[\sqrt{\epsilon}\cot(\sqrt{\epsilon}kt)] \tag{21}$$

Total phase shift:

$$K=\frac{kd}{\cos\theta}-kd-2\tan^{-1}[\sqrt{\epsilon}\cot(\sqrt{\epsilon}kt)] \tag{22}$$

$$\cos\theta=\frac{kd}{K+kd+2\tan^{-1}[\sqrt{\epsilon}\cot(\sqrt{\epsilon}kt)]} \tag{1}$$

Thus knowing d, t, and λ, and assigning a convenient value to K, ϵ as a function θ, or as a function of aperture radius, can be determined.

Figure 4 shows the plot of the above equation for the values of the dielectric constant required for different values of θ for a specific example, where

$$\lambda=3.0 \text{ cm.}$$

$$d=\frac{15}{4} \text{ cm.}$$

$$K=\pi$$

and

$$t=0.5 \text{ cm.}$$

Thus the value of the dielectric constant required at any portion of the dielectric disk **12** in order to produce focusing of a beam as above described can be determined by using the above Equation 1. Although an infinite number of dielectric constant zones would be obtained in solving the above equation for any dielectric disk, it has been found that a relatively few concentric zones are sufficient for obtaining the desired results. For example, for the above mentioned specific example, five concentric rings with dielectric constants decreasing progressively from the center, produce satisfactory results.

The degree of directivity obtainable with a reflector of the above type is substantially that which is achieved with a parabolic reflector having the same aperture. However, for a given restricted space, such as in a streamlined housing, a disk lens reflector can be employed which has a larger aperture radius than a parabolic reflector adapted for use in the same space. This will be further explained hereafter.

Figure 5 illustrates an arrangement in which the reflector **12** is rotated with its axis **42** producing a conical scan, and an illuminating source **40** is located on the spin axis **44**. The illuminating source **40** may be provided with a suitable feed in a well known manner, such as a rear antenna feed **46**, for supplying energy to and collecting energy from the illuminating source **40**. The dotted lines show the antenna reflector **12** in the position it occupies after being turned 180° from the position shown in solid lines; this of course is similar to rotation of a parabolic cylinder having its spin axis angularly displaced from its axis of symmetry to achieve a conical scanning. By spinning the antenna reflector **10** in this manner, a conical surface of revolution will be described by the axis of symmetry **42**, whereby electromagnetic energy may be propagated into or received from the conical region described.

Referring to Figure 6 in a second embodiment of the present invention, a metal reflector element **52** and a dielectric lens element **54** affixed thereto provide an antenna reflector **50** having the configuration of a symmetrical frustrum of a disk, that is, the configuration of a portion of a disk bounded by two parallel planes on opposite sides and equidistant from the center thereof. It should be observed that an antenna reflector having this configuration could be obtained by cutting off segments of the disk reflector **10** in Figure 1 along equal parallel chords. Concentric zones or arcs of dielectric material **14'**, **15'**, **16'**, **17'**, **18'** of different dielectric constants are employed in the manner of the concentric ring portions of the disk re-

flector **10** of Figure 1. Since the reflector element **52** and lens element **54** are symmetrical with respect to their common axis, the antenna reflector **50** will function as a truncated paraboloid reflector for an illuminating source **56** spaced along the axis thereof.

Figure 7 illustrates a reflector **60** having a number of parallel segments **64**, **65**, **66**, **67**, and **68** having dielectric constants which vary in a predetermined manner from the central segment **66**. The dielectric constants of segments equidistant from the central segment **66** may be equal, and may decrease progressively from the dielectric constant of the central segment **66**, in which case the reflector is equivalent, in its behavior and produced results, to a parabolic cylinder. Accordingly, such a lens has a focal line parallel and adjacent to the center segment **66** of such lens; and a suitable source of illumination for such a reflector, such as a line of dipole antennas **69**, would have a locus corresponding to such focal line.

Figures 8 and 9 illustrate a lens reflector **72** having a circular dielectric element **74** of varying thickness and a uniform dielectric constant throughout. The dielectric element **74** has one flat surface and is mounted on a metallic disk **76** with the flat surface of the dielectric element **74** in registry with the metallic disk **76**. An illuminating source **78** having a rear antenna feed **80** is shown located on the axis of the dielectric element **74**. The thickness of the dielectric element decreases from the center toward the periphery to provide equal electrical path lengths for the electromagnetic waves produced by the illuminating source **78**.

Referring to Figure 10 and to the previous mathematical analysis, for a given distance $d=d_0$ from an illuminating source **78'** on the axis of the dielectric element **74** to the center of such element, and a given dielectric constant ϵ, the thickness t_0 at the center of the dielectric element can be determined. For the same dielectric constant ϵ, the thickness t at another portion of the dielectric element **74**, and the distance d from such portion to a plane, perpendicular to the axis of the dielectric element **74**, that includes the illuminating source **78'**, will vary. The total distance from such plane to the metallic disk **76** is constant, and thus

$$d+t=d_0+t_0 \tag{23}$$

or

$$d=d_0+t_0-t \tag{24}$$

Substituting this expression for d in the previous equation, the required thickness t as a function of the aperture radius can be determined, and the equation becomes

$$\cos\theta=\frac{k[d_0+t_0-t]}{K+k[d_0+t_0-t]+2\tan^{-1}[\sqrt{\epsilon}\cot(\sqrt{\epsilon}kt)]} \tag{25}$$

By considering a sufficient number of points, a smoothly varying contour for the wave-incident surface of the dielectric element **74** can be achieved.

Figure 11 shows the plot of the above-mentioned equations in terms of

t vs. r for $t_0=0.5$ cm., $d_0=\frac{15}{4}$ cm., $K=\pi$, $\lambda=3$ cm.

and

$$\epsilon=9$$

The above described types of lens reflectors are characterized in that, for radiant energy to be propagated, they provide a plane phase front at a plane parallel to the flat reflecting surface or aperture of the reflector; for conically scanning an area, each of the above described reflectors and associated illuminating sources preferably would be arranged in the manner described in connection with Figure 5. It is within the scope of this invention, however, that antenna reflectors of the type illustrated in Figures 1 and 2 and Figures 8 and 9 can be arranged to provide a "tilted" plane phase front, i. e., a plane phase front angularly displaced from the aperture of the reflector.

Referring to Figures 12 and 13, there is shown an antenna reflector **100** having a metallic disk **101** upon which is mounted a dielectric element **102** of uniform thickness. An illuminating source or antenna **104** is mounted on the axis of said metallic disk in a suitable manner, as, for instance, in the manner above described. The dielectric element **102** includes a plurality of zones **105—114**, of eccentric circular portions of dielectric material, that is, circular portions whose axes lie in a plane that is perpendicular to and along a radius of the metallic disk **101**. The dielectric constants of the respective zones **105—114**, vary in a predetermined manner from that of the innermost zone **105**. Radiant energy from the antenna **104** which illuminates the dielectric element **102**, and which has a substantially spherical phase front, is selectively delayed by the respective dielectric zones **105—114** so as to emerge in a plane phase front to be propagated in a beam angularly displaced from the axis of the metallic disk **101** toward the spaced centers of the dielectric zones. In this manner, conical scanning can be achieved simply by rotating the reflector **100** about the axis of the metallic disk **101**.

The following mathematical treatment, which will be more readily understood by reference to Figure 14, shows how the dielectric zones of a reflector of the type shown in Figures 12 and 13 may be determined. Referring to Figure 14, a dielectric disk **120** of uniform thickness is initially considered, and the location of a point on the dielectric disk **120**, at which the dielectric constant ϵ is to be determined, is described in terms of the distance, r, of such point from the center of the dielectric disk **120** and the angular distance β of such point from a reference line, $O-y'$. The tilted plane phase front desired for waves with a spherical phase front incident upon the dielectric element **120**, from an illuminating source **122** on the axis of the dielectric element **120**, is indicated at an angle α from the plane of the dielectric element **120**. The total phase shift required for the incident wave at such point may be expressed as

$$K_1=\frac{2\pi}{\lambda}(l_1+l_2)+\phi \tag{26}$$

where

$$l_1=(l-r\cos\theta)\sin\alpha \tag{27}$$

$$l_2=\sqrt{r^2+d^2}-d \tag{28}$$

$$\phi=-2\tan^{-1}\left[\sqrt{\epsilon}\cot\left(\frac{2\pi}{\lambda}t\sqrt{\epsilon}\right)\right] \tag{29}$$

ϕ is obtained in the same manner as above described in connection with Figure 3.

Letting

$$K=K_1-(l\sin\alpha)\frac{2\pi}{\lambda} \tag{30}$$

$$\eta=K+\frac{2\pi d}{\lambda}+2\tan^{-1}\left[\sqrt{\epsilon}\cot\left(\frac{2\pi}{\lambda}t\sqrt{\epsilon}\right)\right] \tag{31}$$

$$\zeta=\frac{2\pi}{\lambda}\sin\alpha \tag{32}$$

then

$$\frac{4\pi^2}{\lambda_2}(r^2+d^2)=\eta^2+r^2\zeta^2\cos^2\beta+2\eta r\zeta\cos\beta \tag{33}$$

Changing to rectangular $(x-y)$ coordinates,

$$r^2=x^2+y^2$$

$$y=r\cos\beta$$

If

$$k=\frac{2\pi}{\lambda}$$

$$y^2[k^2-\zeta^2]+k^2x^2-2\eta\zeta y=\eta^2-k^2d^2 \tag{34}$$

and if

$$\zeta<<k^2$$

which is a valid assumption since α is small, then

$$\left[y-\frac{\eta\zeta}{k^2}\right]^2+x^2=\frac{\eta^2}{k^2}-d^2+\left(\frac{\eta\zeta}{k^2}\right)^2 \tag{35}$$

which is an expression for circles having centers at

$$y=\frac{\eta\zeta}{k^2}$$

$x=0$, and having radii determined by

$$\sqrt{\frac{\eta^2}{k^2}-d^2+\left(\frac{\eta\zeta}{k^2}\right)^2}$$

and such circles represent contours of dielectric constant.

Referring to Figure 15, the reflector **100** is shown mounted within a restricted space, as within a streamlined or tapered housing **124**, for conical scanning. A parabolic reflector **125** is shown in dotted lines as it would be positioned for conical scanning. It can be seen clearly from this illustration that the present invention provides a reflector which can be located in a tapered housing to utilize a much greater amount of space for aperture opening than is possible with a parabolic reflector.

Figure 16 illustrates a reflector having a dielectric element **130** of varying thickness and a uniform dielectric constant for obtaining conical scanning. The dielectric element **130** is mounted with one flat surface in registry with a metallic disk **132**, and a suitable illuminating source **134** is located on the axis of the metallic disk **132**. The thickness of the dielectric element varies in such a manner that radiant energy with a substantially spherical phase front directed through the dielectric element from the illuminating source emerges from the dielectric element to be propagated from a plane constant phase front that is angularly displaced from the axis of the metallic disk **132** a desired amount. By spinning the dielectric element and affixed metallic disk **132** about the axis of such metallic disk, conical scanning will be achieved. Derivation of the surface contour of the dielectric element **130** is given below with reference to Figure 17. The total phase shift may be expressed, as in the preceding analysis, as

$$K_1=\frac{2\pi}{\lambda}[l_1+l_2]+\phi \tag{36}$$

and here,

$$l_1=(l-\cos\beta)\sin\alpha+(t_0-t)\cos\alpha \tag{37}$$

$$l_2=\sqrt{r^2+(d_0+t_0-t)^2}-d_0 \tag{38}$$

$$\phi=-2\tan^{-1}\left[\sqrt{\epsilon}\cot\left(\frac{2\pi}{\lambda}t\sqrt{\epsilon}\right)\right] \tag{39}$$

Letting

$$K=K_1-(l\sin\alpha)\frac{2\pi}{\lambda} \tag{40}$$

as before, but defining

$$\eta=K+\frac{2\pi d_0}{\lambda}-\frac{2\pi}{\lambda}(t_0-t)\cos\alpha+2\tan^{-1}\left[\sqrt{\epsilon}\cot\left(\frac{2\pi}{\lambda}t\sqrt{\epsilon}\right)\right] \tag{41}$$

then for

$$\zeta=\frac{2\pi}{\lambda}\sin\alpha \text{ and } k=\frac{2\pi}{\lambda}$$

as above, we obtain

$$\left(y-\frac{\eta\zeta}{k^2}\right)^2+x^2=\frac{\eta^2}{k^2}-d^2+\left(\frac{\eta\zeta}{k^2}\right) \tag{42}$$

where

$$d=d_0+t_0-t$$

Again, this is an expression for circles; here, however, the circles define contours of constant thickness of the dielectric element.

It should be observed that in each of the foregoing examples, the electromagnetic lens, i. e., the dielectric element, has at least one flat surface provided with means for reflecting such waves directed through the dielectric element toward such flat surface; and the dielectric element has selective transmission characteristics for causing a parallel beam of electromagnetic waves incident upon the dielectric element to be focused, upon emerging from the dielectric element following reflection therethrough from such flat surface, at least at one point adjacent the dielectric element.

What is claimed as new is:

1. An antenna reflector for an antenna system, said reflector including a dielectric element having at least one flat symmetrical surface, and means on said flat surface for reflecting electromagnetic energy radiations passing through said dielectric element toward said flat surface to pass back through said dielectric element, said dielectric element having transmission characteristics, in terms of delay time for electromagnetic energy waves entering said dielectric element along a plane wave front and striking said flat surface, to cause the reflected waves emerging from said dielectric element to be focused at least at one predetermined point in front of said dielectric element.

2. An antenna reflector as defined in claim 1, in which said element comprises a disk of dielectric material of uniform thickness, in which said material includes concentric zones of dielectric constants which vary in steps from the center of said disk toward its rim, and in which said point of focus is on the axis of said disk.

3. An antenna reflector as defined in claim 1, in which said element comprises a disk of dielectric material having a constant dielectric coefficient throughout, in which said element decreases in thickness from the center of said disk toward the rim thereof, and in which said point is on the axis of said disk.

4. An antenna reflector as defined in claim 1, in which said element is a symmetrical frustrum of a disk of dielectric material of uniform thickness, in which said dielectric material includes concentric zones of dielectric constants which decrease in discrete steps from the center of said element toward the periphery thereof, and in which said point is on the axis of said element.

5. An antenna reflector as defined in claim 1, in which said element is a rectangular plate of dielectric material of uniform thickness, in which said material comprises longitudinal layers having dielectric constants which vary in progressive steps from the longitudinal center line of said element toward the longitudinal edges thereof, and in which parallel electromagnetic waves entering said element and reflected back through said element are focused at a plurality of points along a line adjacent to said element.

6. An antenna reflector as defined in claim 1, in which said element comprises a disk of dielectric material of uniform thickness, in which said material has eccentric circular portions of dielectric constants which decrease in progressive steps from the center of said disk toward the rim thereof, and in which said point is displaced from the axis of said disk in the direction of the centers of said eccentric circular portions.

7. An antenna system comprising an illuminating source for producing electromagnetic energy having a substantially spherical phase front, and an antenna reflector for said source, said reflector comprising a dielectric element having at least one flat surface, said dielectric element being disposed adjacent said source so that electromagnetic energy produced by said source passes through said dielectric element to said surface, and a metallic layer on said surface for reflecting said radiations back through said dielectric element, said dielectric element having transmission characteristics in terms of delay time for radiations produced by said source to produce a constant phase front in the radiant energy upon emergence of said energy from said element.

8. A delay lens antenna reflector including a disk of dielectric material having a uniform thickness, metallic means on one flat surface of said disk for reflecting electromagnetic waves directed through said disk toward said one flat surface, and said material having a plurality of concentric zones in which the dielectric constants decrease in progressive steps from the center of said disk in accordance with the function

$$\cos\theta=\frac{\frac{2\pi d}{\lambda}}{K+\frac{2\pi d}{\lambda}+2\tan^{-1}\left[\sqrt{\epsilon}\cot\left(\sqrt{\epsilon}\frac{2\pi t}{\lambda}\right)\right]}$$

where

θ=the angle at which a plane electromagnetic wave entering said disk at each zone must be deflected, upon emerging from said disk after being reflected from said one surface in order to be focused at a point on the axis of said disk,

d=distance of said point from the center of said disk,

K=total phase shift desired,

λ=wave length of said wave in free space,

t=thickness of said disk, and

ϵ=dielectric constant of said disk at the point of entrance of said wave.

9. A delay lens antenna reflector including a disk of di-

electric material of uniform thickness, means on one flat surface of said disk for reflecting electromagnetic waves passing through said disk toward said one surface, and said material including a plurality of zones having characteristic dielectric constants effective to produce the focusing, at a point adjacent said disk, of parallel electromagnetic waves directed through said disk toward said one surface and reflected back through said disk from said one surface.

10. A delay lens antenna reflector as defined in claim 9, in which said zones are concentric, in which the dielectric constants of said zones decrease in progressive steps from the center of said disk toward the rim thereof, and in which said point is on the axis of said disk.

11. A delay lens antenna reflector for an antenna system comprising an electromagnetic wave lens element of dielectric material having at least one flat surface, and said element being supported on a metallic element with said one flat surface in registry with said metallic element, said metallic element being effective to reflect electromagnetic waves directed through said dielectric element toward said one flat surface, said dielectric element having a plurality of zone portions each having a thickness and dielectric constant effective to convert a spherical phase front of electromagnetic energy radiations directed through said dielectric element from at least one radiating source adjacent said dielectric element into a plane phase front of the energy reflected from said one flat surface.

12. A delay lens antenna reflector as defined in claim 11, in which said dielectric element is a disk, said dielectric zone portions are concentric dielectric rings of uniform thickness, said source is on the axis of said disk, and said metallic element is a disk.

13. A delay lens antenna reflector as defined in claim 12, in which the dielectric constants of the respective zone portions of said dielectric element decrease radially in discrete steps from the center of said dielectric disk.

14. A delay lens antenna reflector as defined in claim 11, in which said dielectric element is a symmetrical frustrum of a disk, in which said zone portions are concentric, in which said source is on the axis of said dielectric element, in which said metallic element is a symmetrical frustrum of a disk, and in which the dielectric constants of said concentric zone portions decrease radially in successive steps from the axis of said dielectric element.

15. A delay lens antenna reflector as defined in claim 11, in which said dielectric element is rectangular and of uniform thickness, said zone portions comprise parallel, longitudinal layers of dielectric material, the dielectric constants of said layers on opposite sides of the longitudinal center line of said dielectric element being equal and decreasing in successive steps from said longitudinal

center line, and said source is one of a plurality of radiating sources spaced along said longitudinal center line of said dielectric element.

16. A delay lens antenna reflector including an element of dielectric material having at least one flat surface, and metallic means on said one flat surface for reflecting electromagnetic waves directed through said element toward said one flat surface, said material having a predetermined dielectric constant and a thickness which varies to provide focusing at a predetermined point adjacent said element of a parallel beam of electromagnetic waves which pass through said element toward one flat surface and are reflected back through said element by said reflecting means, the thickness of said element varying in accordance with

$$\cos\theta=\frac{\frac{2\pi}{\lambda}(d_0+t_0-t)}{K+\frac{2\pi}{\lambda}[d_0+t_0-t]+2\tan^{-1}\left[\sqrt{\epsilon}\cot\frac{2\pi t}{\lambda}\sqrt{\epsilon}\right]}$$

where

θ=angle at which a plane electromagnetic wave entering said element must be deflected in order to be focused at said point

(d_0+t_0)=distance between said point and said flat surface

t=thickness of said element where the electromagnetic wave enters said element

K=total phase shift desired

λ=wave length of said wave in free space, and

ϵ=dielectric constant of said element

17. An antenna system comprising an illuminating source producing electromagnetic energy radiations along a substantially spherical wave front, a reflector having a geometric axis of symmetry, said reflector including a flat metallic layer lying in a plane perpendicular to said axis and a dielectric layer in contact with said metallic layer and located between said source and said metallic layer, said dielectric layer being illuminated by said source and having transmission characteristics for transforming said spherical wave front into a plane wave front upon emergence of said radiations from said reflector.

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