

Sept. 22, 1953

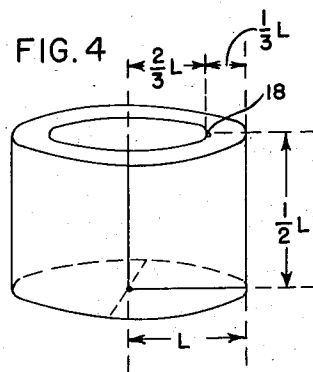
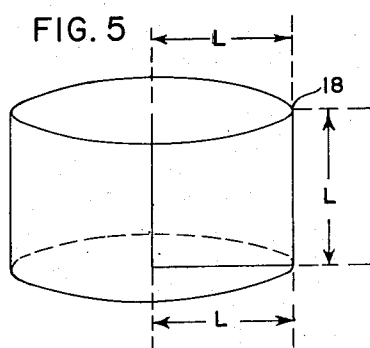
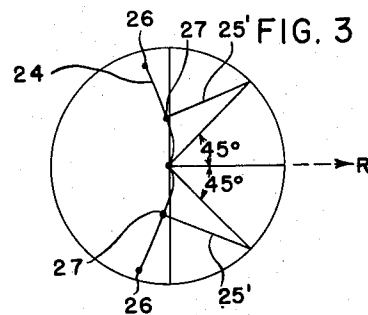
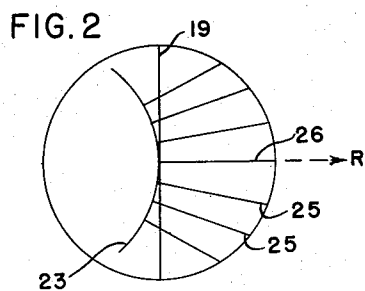
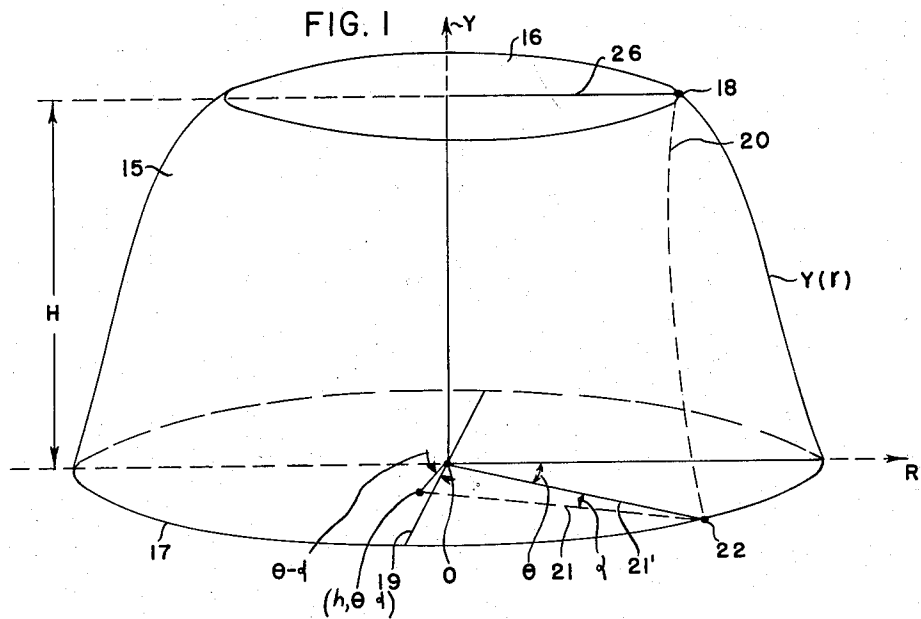
LAN JEN CHU ET AL

2,653,239

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2 Sheets-Sheet 1



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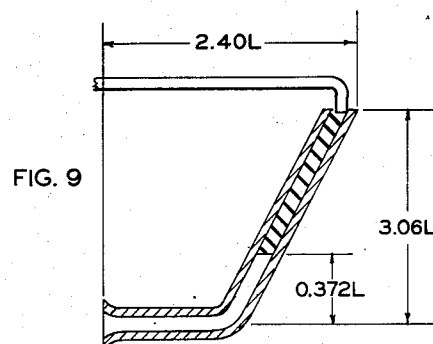
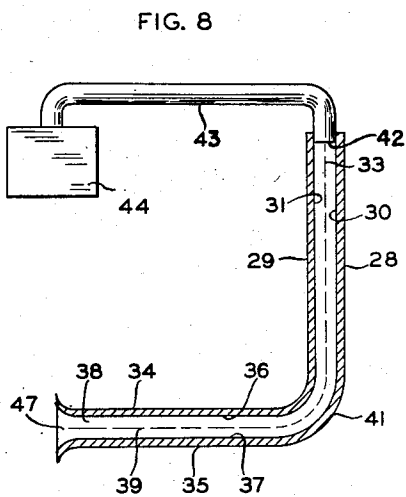
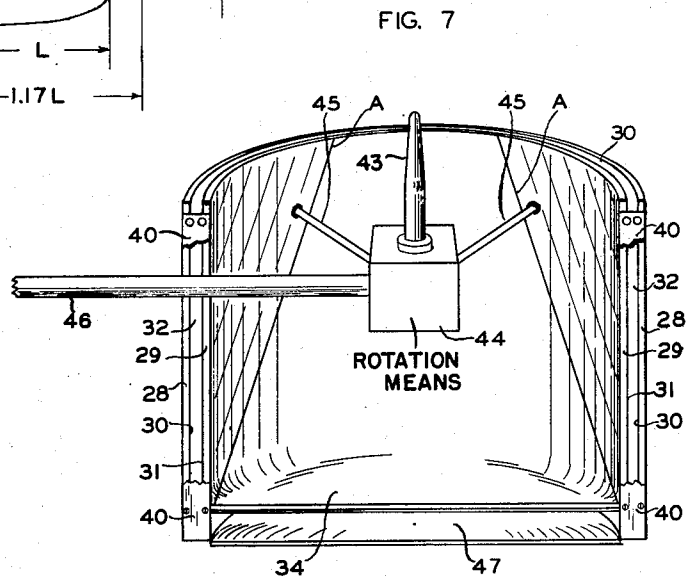
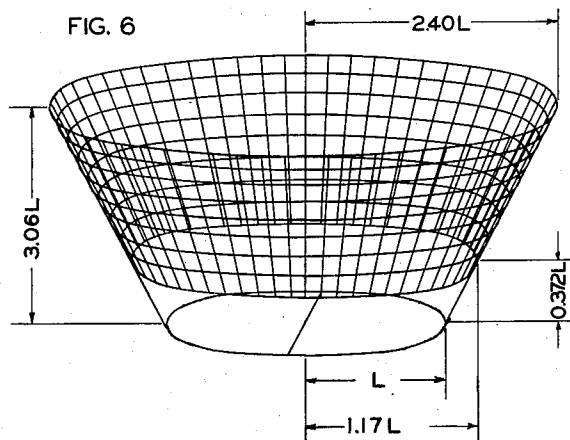
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2 Sheets-Sheet 2



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signments, to the United States of America as
represented by the Secretary of War

Application August 1, 1945, Serial No. 608,298

11 Claims. (Cl. 250—33.63)

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This invention relates to antennae systems and particularly to such systems adapted to radiate or intercept electromagnetic waves in a particular direction.

An object of this invention is to provide means for scanning a sector of space with electromagnetic radiation at a high rate without mechanical movement of the entire antenna. Other objects, advantages, and novel features of the invention will appear more fully herein.

In the drawings:

Fig. 1 is a perspective view illustrating the geometry of the invention;

Figs. 2 and 3 are graphs showing theoretical wave fronts emanating from a theoretical structure of Fig. 1;

Figs. 4, 5 and 6 are perspective views showing some of the possible theoretical structures;

Figs. 7 and 8 are elevational views illustrating an embodiment of the invention, Fig. 8 being partially in cross-section; and

Fig. 9 illustrates in cross-section another embodiment of the invention.

In arriving at means for realizing rapid scanning, it is desirable that the source of radio waves or electromagnetic energy move in a circle, so that rapid scanning may be achieved by rotating a moving part. If rotating parts can be used to feed the energy and cause the resulting scan, it is possible to achieve a higher rate of scan than by oscillating or rocking a member. Secondly, it is desirable that the aperture by which the energy ultimately leaves a wave guide scanning device be a straight line aperture, which may then be used as a source along the focal line of a parabolic type reflector, or emitted directly into space. As the energy feed or source moves, scanning action will then occur in a plane parallel to the line of the aperture. The radiation itself, of course, should have as nearly as possible a straight-line phase front in order to scan a definite sector of space.

The desired results are obtained in the present instance by application of the fundamental assumption that radiation between parallel plates (members affording conductive surfaces separated preferably by less than a half wavelength and having everywhere mutual normals) may be treated as though it follows certain geodesics on a surface median to the conductive surfaces. This hypothesis is common to all parallel plate type wave guides. A geodesic on a surface is a curve having the property that it is the shortest curve joining its end points. As used herein more generally, geodesics are those curves on a

2

surface which minimizes the time required for a point moving on the surface at a defined, possibly variable velocity to travel between given end-points. If the velocity of the point is constant, then the geodesic is the shortest distance on the surface joining the end points. In what follows, reference will be made to radiation as flowing along or following a curve. This, of course, has reference to the manner in which the radiation may be studied as though it followed geodesics on the median surface between parallel plates.

Referring now to Fig. 1, there is illustrated the geometry involved in a specialized solution of the problems relevant to the present invention. The velocity of radiation is assumed constant. The origin of the coordinate system is point O. Y and R are mutually perpendicular axes. A surface of revolution 15 is formed by rotating a given curve $y(r)$ disposed in the Y—R plane about the Y axis. Circles 16 and 17 form boundaries at the top and bottom of the surface. r_0 is the length of radius 26 of circle 16 in the Y—R plane terminating at a hypothetical point source of radiation 18. Diameter 19 of circle 17 is perpendicular to axis O—R.

Radiation from source 18 is assumed to flow along paths such as dotted curve 20 on surface 15 to circle 17, thence following a straight line path such as 21 toward diameter 19. h is the distance from origin O to line 21. θ is the angle between axis O—R and radius 21' extended to the point 22 at which radiation following the path 20 enters the base plane of circle 17, thence following the path 21. α is the angle between 21' and line 21. r_1 is the radius of circle 17.

By application of formulae developed in the calculus of variations, angles θ and α have the following values:

$$(1) \quad \theta = \int_{r_0}^{r_1} \sqrt{1 + \left(\frac{dy}{dr}\right)^2} \frac{dr}{r \sqrt{r^2 - h^2}}$$

$$(2) \quad \alpha = \arcsin h/r_1$$

Therefore, the difference between these angles will be:

$$(3) \quad \theta - \alpha = \sum_{n=1}^{\infty} A_{2n-1} \frac{L^{2n-1}}{(2n-1)!} h = 1, 2, 3 \dots$$

where

$$(4) \quad A_{2n-1} = (2n-1) \int_{r_0}^{r_1} \frac{\sqrt{1 + \left(\frac{dy}{dr}\right)^2}}{r^{2n}} dr - \frac{1}{r^{2n-1}}$$

and the positive sign is taken for the radical

The function $y(r)$ may now be chosen as best suits the purpose. Further, the curve defined by the end-point of h away from the origin, expressed in polar coordinates as $(h, \theta - \alpha)$ in the plane of circle 17, traces a wave front, since it is everywhere normal to the direction of propagation. This curve is defined by Equation 3.

It is apparent from the geometry and the symmetry of the figure involved that it is sufficient to consider radiation from only one source.

An examination of Equation 3 reveals that there are two types of wave fronts. One type is shown as curve 23 in Fig. 2, for $A_1 \geq 0$. The other type when $A_1 < 0$ is shown in Fig. 3 as curve 24. The direction of radiation toward diameter 19 is shown in Figs. 3 and 4 as lines 25 and 25' respectively.

If the condition that no value of r exceeds r_1 is imposed, an optimum configuration which will give most nearly a straight-line phase front may be shown by the above formulae to be a right circular cylinder, having a height:

$$(5) \quad H = r_1^2 \left(\frac{2}{r_1} - \frac{1}{r_0} \right)$$

The appearance of a surface of revolution calculated according to this formula is illustrated in Fig. 4. It has a base of radius L and a top radius of $\frac{2}{3}L$, the height H of the cylindrical surface being $\frac{1}{2}L$. Included in the surface of revolution is the area lying between two concentric circles, one of radius $\frac{2}{3}L$ and one of radius L in the plane of the circle on which the radiating source is located.

Another surface, calculated by formula (5) is illustrated in Fig. 5. It consists of a right cylinder of height L and radius of base L . Point source 18 is located on the circle enclosing the top of the cylinder. Since the optics improve as r_0 is increased, as is evident from Equations 3 and 4, the surface of Fig. 5 is optically better than that of Fig. 4.

The wave front resulting from employment of a cylindrical surface calculated in accordance with Equation 5 is of the type shown in Fig. 2. By decreasing H slightly, the effect is to change the wave front to the type illustrated by Fig. 3. Although Equation 5 gives the optimum solution over the entire diameter, it is better to slightly reduce the height H where consideration is restricted, for example, to the radiation pattern for $-45^\circ \leq \theta \leq 45^\circ$, because the fact that the extreme points 26 of curve 24 are so far from straight line phasing need not be considered. Consideration is limited to the phasing between points such as 27, as shown in Fig. 4 which are now the extreme points of the portion of curve 24 to which attention is directed.

A still further improvement in the system may be obtained by the use of a dielectric. The phase front resulting from use of a dielectric may be studied by suitable alterations in the equations hereinbefore mentioned, which give effect to the change in velocity of the radiation traveling along the surface, or of the hypothetical moving point, thereby changing the geodesic along which radiation travels between given end-points.

As an example, referring to Fig. 6, there is illustrated a figure in which the shaded portion has an index of refraction of 1.6. The proportions are calculated from the altered formulae to give a nearly straight line phase front.

Figs. 7 and 8 illustrate an embodiment of the invention. Members 28 and 29 afford conductive substantially parallel surfaces 30 and 31, respectively, each shaped as a half right cylinder to

form wave guide 32. Their separation is preferably less than a half wave length throughout. The hypothetical surface 33 median to surfaces 30 and 31 thus forms a half right cylinder. Members 34 and 35 afford conductive substantially parallel surfaces 36 and 37, respectively, semi-circular in shape and forming wave guide 38. Hypothetical surface 39 is median to surfaces 36 and 37. Member 34 is joined to member 29 and member 35 to member 28, so that, substantially, surface 37 is a base of the half right cylinder formed by surface 30, surface 36 is a base of the half right cylinder formed by surface 31, and median surface 39 is a base of the half right cylinder formed by median surface 33. Members 28, 29, 34 and 35 are held in fixed relationship by means such as plates 40, whose inner surfaces may be of material absorptive of the energy to prevent interfering reflections.

As will be understood by those skilled in the art, it is desirable that reflection be minimized at the bend 41 where waveguides 32 and 38 communicate, so that standing waves will not result with an accompanying loss of the energy which is transmitted from one waveguide to the other. A toroidal shape is usually sufficient for practical purposes. Other configurations may be used, of course. In practice, it is usually not necessary to consider the effect on the wavefront of bend 41, if its cross-sectional dimensions are small compared to the diameter of base surface 39 and height of cylindrical surface 33, because the high degree of accuracy necessary in optical systems is ordinarily not required in cognate systems involving electromagnetic radiation. If required, a prediction of the wavefront may include the bend by employing Formula 4 or 9.

To provide a source of radiation, a waveguide 43 has its termination 42 inserted into waveguide 30 at the top thereof. Housing 44, supported by suitable means such as members 45, contains means for rotating waveguides 43, including a rotating joint for feeding energy into it from a waveguide 46, and, if desired, may include means for transmitting information of the relative angular position of waveguide 43. Two or more waveguides 43, with suitable switching means such as disclosed in copending application of Lan J. Chu, Ivan A. Getting and Henry A. Strauss Serial No. 535,856, filed May 16, 1944, now Patent No. 2,549,721 issued April 17, 1951, may be used, and by rotating these continuously, a very rapid scanning by radiation from aperture 47 will result. Aperture 47 should be shaped to give proper impedance match from waveguide 38 to space, or to a reflector, if the aperture illuminates one.

As waveguide 43 rotates, a line to its projection on surface 39 (extended) from the center of the line of aperture 47 will make an angle with the line of aperture 47. If this angle is too great, there will be undesirable results due to the smaller effective length of aperture 47. Therefore, radiation from 44 should be restricted to the periods when the angle mentioned lies within limits, say within 45° from the normal to the line of aperture 47. At its extreme positions, under this limitation, the aperture obviously has an effective length that is approximately $\frac{1}{2}$ its actual length, because one side of the phase front is partially blocked.

Furthermore, an additional advantage of the invention lies in the fact that the major portion of the energy will emanate from the central portion of the diametral opening. Therefore, the amount of energy lost when radiation leaves the aperture in a direction other than that normal

5

to the line of aperture 47 is less than would be indicated by the approximate effective length noted above. This advantage appears to be inherent in other embodiments of the invention.

Only part of wave guide 32 may be utilized to guide radiation if the angle of scanning is restricted, and then it would be possible to omit the portion of wave guide 32 not used, for instance, the part shown shaded in Fig. 7, energy being fed from aperture 43 only while it lies within the sector denoted by lines A.

Fig. 9 displays in cross-section a wave guide scanning device employing a dielectric having a refractive index of 1.6. The dimensions shown are calculated as in Fig. 6, thus providing a wave front nearly straight. Cross hatching represents the dielectric material inserted in the waveguide. Comparison of Fig. 9 with Fig. 6 illustrates how a device may be built on the basis of the theoretical equations.

Any semi-surface of revolution may be chosen for the median surface between the walls of a waveguide, and the wave front emanating from the base diameter aperture may be calculated as shown by the use of the formulae.

By choosing appropriate values for the dimensions, and by using, if desired, an appropriate dielectric, the wave front may be made to differ from a straight line by as small an amount as desired. That is, the difference $\theta - \alpha$ may be made to remain less than an arbitrary preassigned constant. Thus, the theoretical wave front may be made to approach a straight line within limits smaller than errors resulting from differences in construction due to permissible tolerances.

Still another variation may be accomplished by combining the use of a refractive lens with the type of structure disclosed herein. The lenses are highly useful in reducing the bulk and size of the equipment. This combination is the subject of copending application by C. V. Robinson, Serial No. 608,299 filed August 1, 1945.

Although the discussion herein has been directed to the transmission of energy from a source, a converse effect permits the same structure to be used in the reception of radiation with similar directive properties, as is well known in the art.

It is apparent that so many variations in this type of scanning device are possible without departing from the scope or spirit of the invention that it is impractical to discuss each one in detail. Therefore, it is not intended to restrict the claims to the precise embodiments herein disclosed.

What is claimed is:

1. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a half right-circular cylinder including a semi-circular base thereof, said half right-circular cylinder having a height substantially equal to the radius of its base, the base portions of said two members being semi-circular plates having a radiating aperture therebetween.

2. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a half right circular cylinder including

6

a semi-circular base thereof and also including a portion of the top thereof, said half right circular cylinder having substantially the proportions determined by the formula:

$$H = r_1^2 \left(\frac{2}{r_1} - \frac{1}{r_0} \right)$$

wherein H is the height of said cylinder, r_1 is the radius of said cylinder, and r_0 is the radius of a circle in the plane of the top of said cylinder and concentric therewith, such that the portion of the top included in said median surface lies between the said circle of radius r_0 and the circle of radius r_1 forming the top.

3. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a surface of revolution including a substantially semi-circular base thereof, the base portions of said two members being semi-circular plates having a plane radiating aperture therebetween.

4. The combination of claim 3, including a rotatable source of electromagnetic energy coupled to said waveguide and means for rotating said source along a locus in said waveguide remote from the base thereof.

5. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a surface of revolution including a substantially semicircular base thereof, a rotatable source of electromagnetic energy adapted to propagate energy in a direction along said median surface and means for causing said source to rotate about the axis of said surface of revolution whereby electromagnetic energy entering said waveguide from said source is caused to scan a sector of space with electromagnetic radiation.

6. In an apparatus for scanning a sector of space with electromagnetic radiations a first waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a surface of revolution including a substantially semicircular base thereof, a second waveguide rotatable about the axis of said surface of revolution, said second waveguide terminating adjacent the upper circumference of said first waveguide in an open end adapted to propagate electromagnetic energy in a direction along said median surface, means for supplying energy to said second waveguide and means for rotating said second waveguide whereby energy emitted from said first waveguide is caused to scan a sector of space with electromagnetic radiations.

7. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a surface of revolution including a substantially semicircular base thereof, and solid dielectric material completely filling a portion of the space between said two members and adapted to alter

the phase front of energy radiated by said waveguide, the base portions of said members being a pair of semi-circular plates having a radiating aperture along the diametrical edges of said semi-circular plates.

8. In an apparatus for scanning a sector of space with electromagnetic radiation, a waveguide formed of two members affording conductive substantially parallel surfaces, said members being so shaped that the median surface between said parallel surfaces is substantially a portion of a surface of revolution generated by the revolution of a segment of a straight line about a coplanar axis, said segment lying between a first and a second plane perpendicular to said axis, the distance from said axis to the point of intersection of said segment with said first plane being a preselected distance L, the spacing between said two planes along said axis being 3.06 L and the distance from said axis to the point of intersection of said segment with said second plane being 2.40 L said median surface including a substantially semicircular base in said first plane, and solid dielectric material having a refractive index of 1.6, said dielectric material completely filling said waveguide between said second plane and a third plane parallel to said first plane and

closer to said second plane by a distance along said axis equal to .372 L.

9. The apparatus of claim 2, wherein r_0 is equal to $\frac{2}{3} r_1$, and H equals $\frac{1}{2} r_1$.

10. The apparatus of claim 5, further including means for limiting the entrance of energy into said waveguide from said energy source to a given angular sector about the center of said waveguide, the vertex of said sector being said axis of said surface revolution.

11. The apparatus of claim 10, wherein said angular sector is equal to 45°.

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