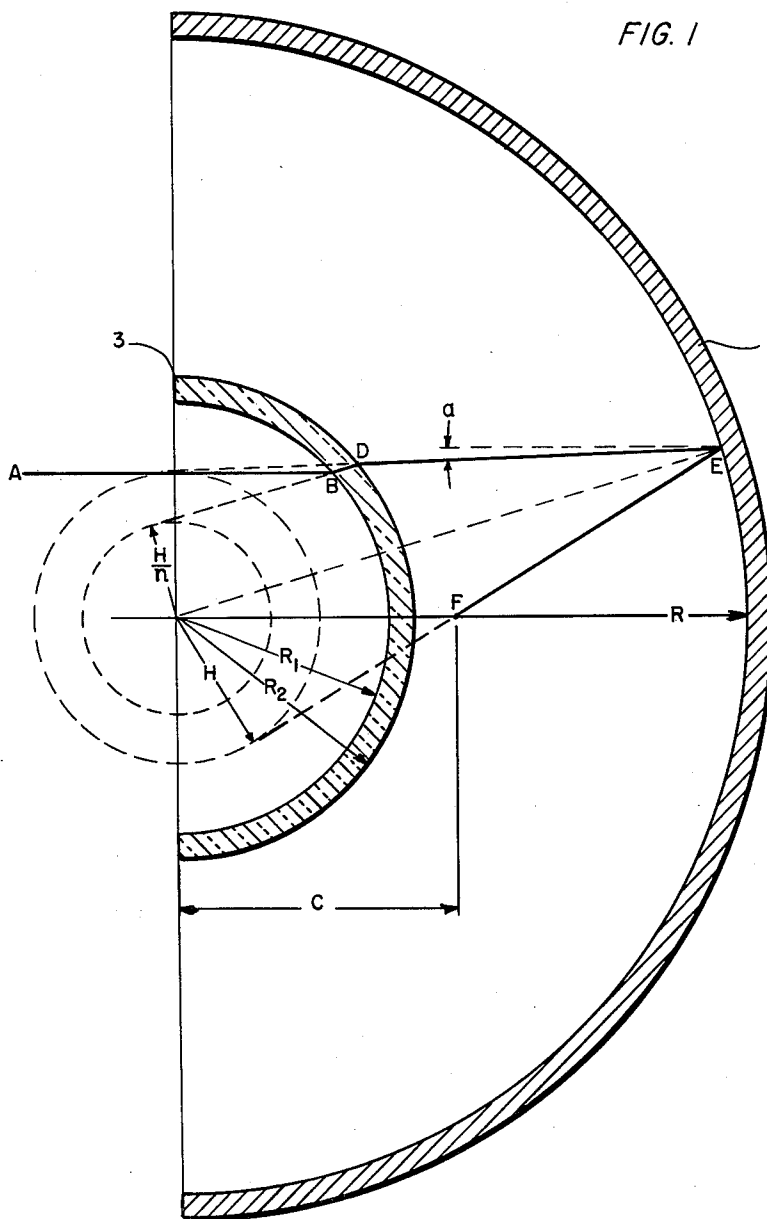


3,071,768

RAPID SCAN ANTENNA WITH LENS FOR CORRECTION OF ABERRATION

4 Sheets-Sheet 1



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3,071,768

RAPID SCAN ANTENNA WITH LENS FOR CORRECTION OF ABERRATION

Original Filed Dec. 30, 1953

4 Sheets-Sheet 2

FIG. 2

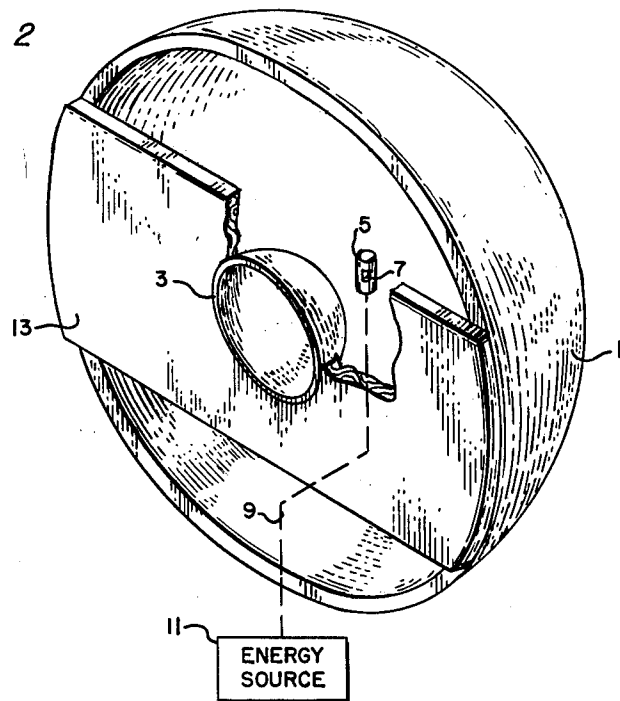
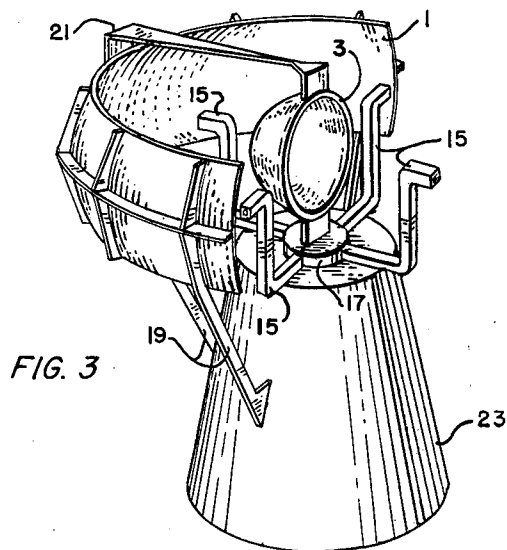


FIG. 3

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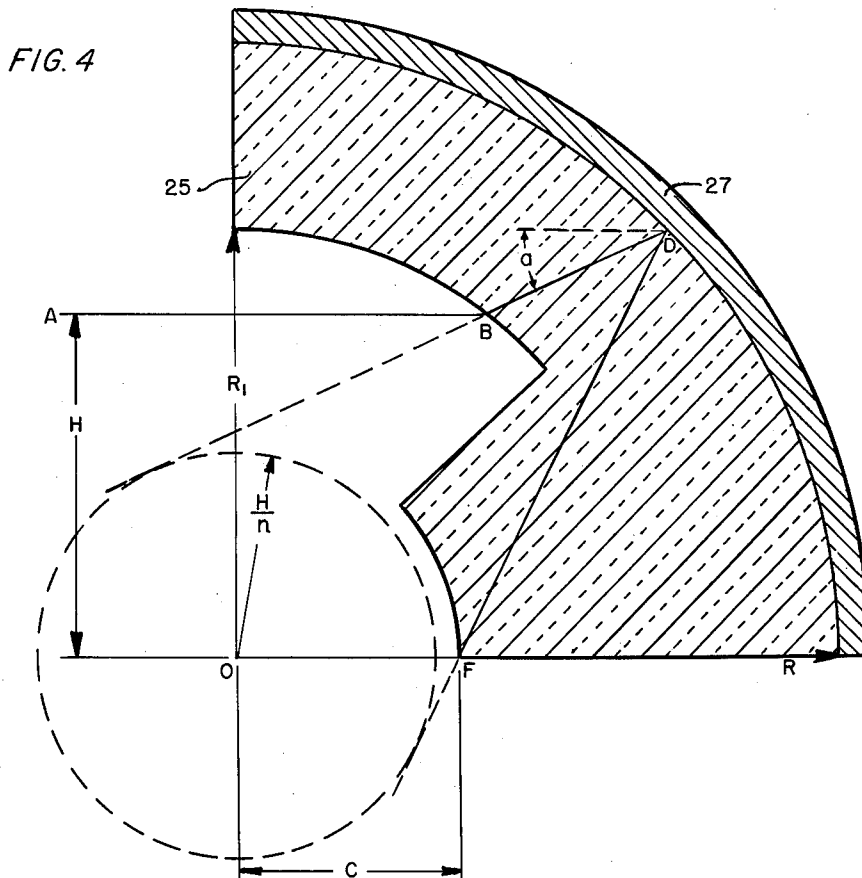
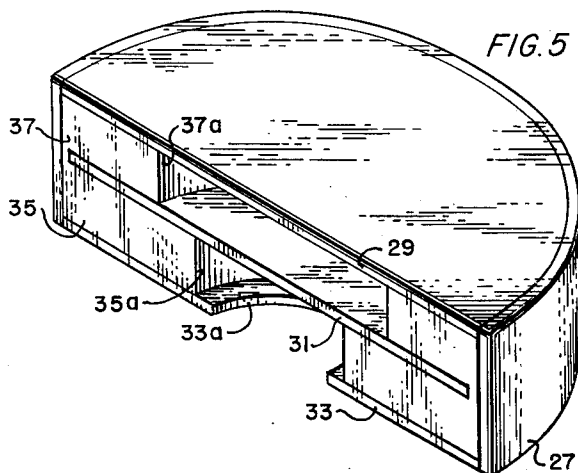
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RAPID SCAN ANTENNA WITH LENS FOR CORRECTION OF ABERRATION

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4 Sheets-Sheet 3



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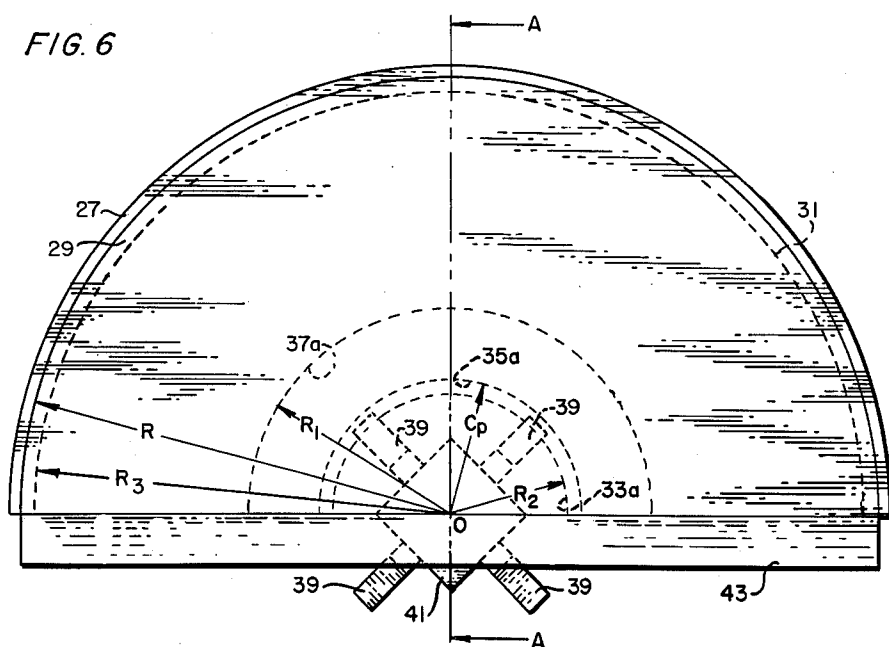
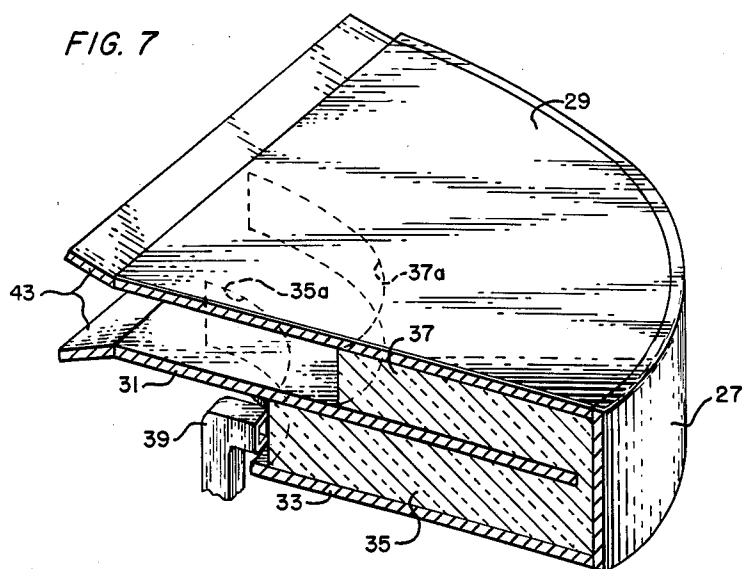
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RAPID SCAN ANTENNA WITH LENS FOR CORRECTION OF ABERRATION

Original Filed Dec. 30, 1953

4 Sheets-Sheet 4



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3,071,768

RAPID SCAN ANTENNA WITH LENS FOR CORRECTION OF ABERRATION

Allen S. Dunbar, Palo Alto, Calif., assignor to the United States of America as represented by the Secretary of the Army

Original application Dec. 30, 1953, Ser. No. 401,439. Divided and this application Oct. 4, 1960, Ser. No. 67,869

4 Claims. (Cl. 343—754)

This invention relates to rapid scan, highly directive antennas for directing microwave electromagnetic energy, and particularly to such antennas that are suitable for use in radar equipment.

This application is a division of application Serial No. 401,439, filed December 30, 1953, now abandoned.

A rapid scan antenna may be defined as a highly directive antenna whose beam can be made to scan rapidly through a specified volume of space by some means other than the motion of the antenna as a whole. Such antennas are frequently used in tactical applications of radar, where it is required that the directive beam of the radar antenna scan rapidly and uniformly throughout a given volume of space, so that the position and direction of motion of moving targets may be determined. In some cases, such antennas are also used in radar equipment in order to track targets.

One problem to be overcome in rapid scan antennas is to find some means by which a directive radar beam may be made to scan a specified volume of space at a rate which would be excessively rapid, due to inertia, if mechanical linkages alone were used.

Another problem in such antennas is that they require some device which will transform the pattern of a partially directive elementary radiator to a directive beam. This device may be a reflector, and directivity is obtained merely by producing a uniform phase front over a large effective reflector aperture.

Scanning also imposes restrictions upon the directive system, for now the system must be not only directive but also wide-angle, in the sense that the directivity is not impaired by motion of the beam with respect to the antenna aperture. Such wide-angle performance, however, can be had only at the price of a reduction in directivity. Since a reduction in directivity implies a reduction in the gain of the antenna, the price paid for scanning is less efficient use of the antenna aperture.

Still another problem is that of the f -number of the reflector. Since the f -number is defined as being the ratio of the focal length of the reflector to the effective aperture of the reflector, it will be seen that the smaller the f -number of any given reflector, the closer its feed system can be. This is a factor of greatest importance in antenna design, and this is the factor that creates one of the major difficulties in this art, since it is desired to obtain an antenna reflector with a small f -number, but all such systems inherently have a narrow field.

In attacking the foregoing problems, it was decided to provide such an antenna by using a reflector having a reflecting surface with a cross-sectional shape that is a portion of a circle. Such a reflector, because of its symmetry, can be used to direct energy parallel to its axis when an energy source is placed at its focus. While such an antenna reflector could be used to provide a directive beam of energy, aberrations exist due to its failure to come to a perfect focus. Such aberrations provide a limit for the field of any antenna reflector of short focal length. While such a reflector is adequate, despite aberration, for an antenna system operating at $f/1$ or greater, at smaller f -numbers the aberration becomes too great for satisfactory antenna performance. The present invention corrects such an antenna reflector and pro-

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vides an antenna having an f -number that is less than one and having very little aberration.

It is therefore one object of this invention to provide a directive antenna for microwave electromagnetic energy which will scan rapidly over a wide angle with a minimum of aberration.

Still another object of this invention is to provide a directive microwave antenna that has a high gain and is capable of rapidly scanning a wide sector in space.

Yet another object of this invention is to provide a directive rapid scan microwave antenna having very little aberration and an extremely small f -number.

These objects are accomplished by providing a reflector having a reflecting surface with a cross-section that is a portion of a circle, correcting the aberration therein by placing a coaxial corrective dielectric lens before said reflector, the lens serving to correct said aberration, and by having a rotatable feed system disposed near the focal point of the reflector-lens combination.

For a better understanding of the invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings, in which:

FIG. 1 is a cross-sectional view of an embodiment of the invention, and illustrates the geometry of the invention;

FIG. 2 is a perspective view of one embodiment of the invention with one element broken away to show the feed system;

FIG. 3 is a perspective view of another embodiment of the invention;

FIG. 4 is a cross-sectional view of another embodiment of the invention and illustrates the geometry of this embodiment of the invention;

FIG. 5 is a perspective view of a portion of another embodiment of the invention, incorporating the principles of the embodiment of FIG. 4;

FIG. 6 is a top view of the embodiment shown in FIG. 5 and includes additional elements; and

FIG. 7 is a cross-sectional perspective view taken along line A—A of FIG. 6.

Referring now to FIG. 1, this figure illustrates the geometry of the present invention. There is shown in this figure, in cross-section, a hemispherical reflector 1 having a radius R . It is well known that in such a reflector, rays entering parallel to the axis and striking the reflecting surface will be focused at the half radius point along the axis. However, since perfect focus is impossible, these parallel rays do not pass through a single point but rather describe a region of approximate focus. This failure of a spherical reflector to focus parallel rays of energy through a single point is called spherical aberration, and this aberration has a given sign. A close examination of the region of approximate focus shows that there is a place where the density of the rays is greatest or where the rays most nearly approach a focus. This place is called the circle of least confusion and is the place at which the aberration is one-quarter the spherical aberration at the half radius point. In order to provide an antenna reflector having a small f -number and having a permissible amount of aberration, it has been found necessary to introduce spherical aberration of a sign opposite to that of the reflector. By introducing a hemispherical dielectric lens 3 concentrically and coaxially within reflector 1, so that they have a common center point O , the circle of least confusion can be reduced to a very small value and will occur at a point along the axis of the reflector 1 which will be determined by the index of refraction n , and the dimensions, of corrector lens 3. Examining now the structure of FIG. 1, the path of a ray of electromagnetic energy entering lens 3 parallel to the axis thereof will be considered. Such a ray enters lens

3 at a height H above the common axis of both the lens 3 and the reflector 1. This ray is therefore shown as being tangent to a dashed line circle having a radius H . This ray, labelled A, strikes lens 3 at point B, is refracted, and leaves the lens at point D. Upon leaving the lens, the path of this ray changes once more and the ray then strikes the reflecting surface of reflector 1 at a point E. The line D—E forms an angle a with a dashed line drawn through point E parallel to the axis of the reflector. The ray is then reflected by reflector 1 and passes through a point F on the axis of the reflector. Point F corresponds approximately to the position of the circle of least confusion mentioned above. Extending line E—F by means of a dashed line, it will be seen that it is tangent to the dashed circle having a radius H . Further, extending line B—D back toward the center O by means of a dashed line, it can be shown that it is tangent to a dashed circle having a radius equal to H/n . The point at which line E—F crosses the axis of this system is a distance C from the center point O of the system. This distance C is the point at which rays of energy entering the system will cross the axis. The paraxial value of C, C_p , the axial point crossed by rays entering parallel to the axis, is given by:

$$\frac{1}{C_p} = \frac{1}{F} + \frac{1}{f} \quad (1)$$

where F is the focal length of the reflector (half its radius), and f is the focal length of the corrector. The latter is given by the relation:

$$\frac{1}{f} = \frac{n-1}{n} \left[-\frac{1}{R_1} - \frac{1}{R_2} \right] \quad (2)$$

where R_1 is the inner radius of corrector lens 3 and R_2 is its outer radius.

In order to obtain good correction, it is necessary that C for any given ray should coincide with or differ only slightly from its paraxial value, C_p . Consequently, C must be computed as a function of R_1 , R_2 , and the ray height H . For FIG. 1 it may be seen that:

$$C = \frac{H}{\sin \left[2 \sin^{-1} \left(\frac{H}{R} \right) + a \right]} \quad (3)$$

The value of the angle a is given by:

$$a = \sin^{-1} \left[\frac{H}{R_1} \right] - \sin^{-1} \left[\frac{H}{R_2} \right] - \sin^{-1} \left[\frac{H}{nR_1} \right] + \sin^{-1} \left[\frac{H}{nR_2} \right] \quad (4)$$

Using Formulas 1 to 4, and given a reflector having a given radius R and a lens made of material having a given index of refraction n , C and C_p may be calculated for various values of R_1 and R_2 at any given H . Values of R_1 and R_2 are then selected for which, at some maximum H , C and C_p substantially coincide. H should be as large as possible since $2H$ is the effective aperture length of the reflector-lens combination. For a material having an index of refraction n equal to 1.6 (polystyrene, Plexiglas), a reflector having a radius R equal to 30", and an H equal to 0.30R or 9.00", a satisfactory system has been built with R_1 equal to 0.36 R or 10.8", R_2 equal to 0.410 R or 12.30", and the distance F of the focus from the center point O of the reflector equal to .470 R or 14.10". In this particular system, C_p differed from C by only .0049 R or 0.14", the circle of least confusion was less than $\frac{1}{40}$ the size of the circle of least confusion in the same spherical reflector without correction, and the f -number was 0.78.

Referring now to FIG. 2, there is shown the reflector 1 and the lens 3 discussed in connection with FIG. 1. Further, there is shown a rotatable directive feed source 5 disposed between the lens and the reflector. This feed source may be of the rotary switch type disclosed in

volume 39, No. 12 (1951) of the Proceedings of the I.R.E., pages 1566 to 1567, by M. W. Long. This rotary switch permits the rapid scanning of a given angular sector of the reflector. A plurality of orifices 7 are within rotary switch 5 and form the exit for energy leaving switch 5 and projected toward the inner surface of reflector 1. The size of these orifices determines the angular sector scanned. An energy source 11 is connected through a coupling 9 to the rotatable switch 5, and serves to feed said switch with microwave electromagnetic energy. In order to further reduce the aberration of this system, a stop 13 is placed across the mouth of reflector 1, the corrector lens 3 being supported thereby and passing therethrough. This stop may be made of any material which will not pass electromagnetic energy, such as plywood. The feed source 5 is placed at the circle of least confusion, substantially at the focus C_p or C, and serves to scan a given angular sector of the inner surface of the reflector 1, energy leaving the lens 3 parallel to the axis of the system.

FIG. 3 shows another embodiment of the invention. In this figure there is also shown the spherical reflector 1 and the corrector lens 3. The lens 3 is firmly held by a support 21, which is in turn attached to the back of reflector 1. The reflector 1 is supported by three arms 19, which arms are supported in turn by a base 23. Four rotatable feed horns 15 are provided, and these horns lead into a rotary switch 17. The mouths of horns 15 are disposed on a circle having a radius from the common center point of reflector 1 and lens 3 that is substantially equal to C_p or C. This rotary switch only permits energy to be passed through each horn 15 when it is within a given angular sector within reflector 1. A rotary switch suitable for use in this invention is depicted on page 58 and explained on pages 55-59 of volume 26 of the Radiation Laboratory Series, entitled "Radar Scanners and Radomes," published by McGraw-Hill in 1948. The principles of this embodiment are clearly the same as those illustrated in the embodiment shown in FIG. 2, the two systems differing only in that different feed systems are provided, the system of FIG. 2 lending itself to the addition of a stop.

The principles of the present invention may also be embodied in an antenna in which the dielectric antenna lens is placed directly against the reflector. Referring to FIG. 4, the geometry of such a system is exemplified. In this figure, half of a dielectric lens 25 is shown. This lens has an index of refraction equal to n . The outer circumference of this lens is directly in contact with the inner surface of a cylindrical reflector 27, only half of which reflector is shown in FIG. 4. The inner surface of reflector 27 and the outer surface of the lens 25 have a radius R , one inner surface of the lens having a radius R_1 , as measured from a center point O. A ray of electromagnetic energy A entering the system at a height H above the axis will strike one inner surface of the lens 25 at point B, will be refracted to strike the inner surface of reflector 27 at point D, and will be reflected to cross the axis of the system at point F. Point F is a distance C from the center point O of the system. It may be shown that extensions of lines B—D and D—F toward the center of the system, as shown by dashed lines, will be tangent to a dashed line circle having a radius equal to H/n . In order to ensure that the ray of energy remains within the lens, the lens should have the shape shown in this figure, with the other inner surface of the lens having a radius C.

With the aid of the construction of FIG. 4, it may be seen that the angle a which the reflected ray makes at point D with a dashed line parallel to the axis of the system is given by:

$$a = \sin^{-1} \left[\frac{H}{R_1} \right] - \sin^{-1} \left[-\frac{H}{nR_1} \right] \quad (5)$$

Further, it may be seen that:

$$C = \frac{\frac{H}{n}}{\sin \left[2 \sin^{-1} \left(\frac{H}{nR} \right) + a \right]} \quad (6)$$

The paraxial value of C , C_p , is given by:

$$C_p = \frac{1}{2/R + (n-1)/R_1} \quad (7)$$

The focal length of this system is given by:

$$\frac{1}{F} = \frac{2}{R} \left[1 + \frac{n-1}{n} \left(\frac{R-R_1}{R_1} \right) \right] \quad (8)$$

In order to avoid having energy pass through the thick portion of lens 25 twice when H is equal to or less than C , thereby producing a shadow effect, a more practical construction than the embodiment shown in FIG. 4 has been made. Since the embodiment of FIG. 4 particularly lends itself for use in a pillbox type of construction, such a construction is shown in FIG. 5. In this figure is shown a double layer pillbox formed by a top plate 29, a middle plate 31, and a bottom plate 33, and bounded by a cylindrical reflector 27. The reflecting surface of reflector 27 bounds the pillbox and is a portion of a cylinder having a radius R , top and bottom plates 29 and 33 being portions of a disk also having a radius R . Middle plate 31 is a portion of a disk having a radius substantially less than R . Between plates 29 and 31 lies a portion of a cylindrical dielectric lens 37 having a semicircular portion 37a cut out therefrom. Between plates 31 and 33 lies another portion of said lens labelled 35 and having a semicircular portion 35a cut out therefrom. Plate 33 also has a semicircular portion 33a cut out therefrom. Lens 35—37 is coaxial and concentric with reflector 27, and introduces aberration opposite in sign to that of the reflector. The outer circumference of the lens has the shape of a portion of a cylinder with a radius R , and is in electrical contact throughout its extent with the reflector. The top half of the lens, labelled 37, has the cross-sectional shape of a portion of an annulus, as has the bottom half, labelled 35.

Referring now to FIG. 6, this figure shows a top view of the antenna shown in FIG. 5, corresponding numerals denoting like elements. This figure, in addition, includes a rotary switch and source of microwave electromagnetic energy 41 disposed at the center O of the lens and four feed horns 39 attached thereto and rotated thereby. These elements 39 and 41 respectively are like elements 15 and 17 of FIG. 3. Reflector 27 is shown as having an inner radius R , dielectric element 37 is shown as having an inner radius R_1 , dielectric element 35 is shown as having an inner radius C_p , plate 31 is shown as having a radius R_3 , and plate 33 is shown as having an inner radius R_2 . Further, a pair of vanes 43 are used to direct the electromagnetic energy emanating from this system. It should be understood that the switch disclosed in the aforementioned I.R.E. publication could be used to replace elements 39 and 41.

Referring now to FIG. 7, there is shown a view taken along line A—A of FIG. 6. Corresponding numerals in this figure represent identical elements with those in FIGS. 5 and 6. In this figure, it will be apparent that the waveguide horns 39 direct energy through dielectric portion 35 and out through dielectric portion 37 through vanes 43. With this pillbox type of antenna, the mouths of the waveguide horns 39 travel between parallel plates 31 and 33 on a constant radius approximately equal to C_p and in close proximity with the dielectric portion 35, thus causing a scanning by the radiated beam of electromagnetic energy. Rotary switch 41 only permits energy to enter each horn 39 when it is within a given angular sector within the pillbox. As will be seen from this figure, middle plate 31 has a radius substantially less than the radius of top and bottom plates 29 and 31, in order

to enable energy from horn 39 which passes through the lower lens portion 35 to be reflected by reflector 27 into upper lens portion 37.

In an antenna constructed as shown in FIGS. 5 to 7, a reflector radius R equal to 18" was used, and a lens made of polystyrene and having a refractive index n equal to 1.6 was made up. Using Formulas 5 to 8, C and C_p may be calculated for various values of R_1 and H . A value of R_1 is then selected at which C and C_p will substantially coincide and H is a maximum, $2H$ being the effective aperture of the antenna system. R_1 was found to have a value of 0.470 R or 8.46" when H was equal to 0.40 R or 7.20", and C_p was equal to 0.305 R or 5.49", R_2 being chosen, for convenience of construction, equal to 5.00". The radius R_3 of the middle plate 31 was chosen at a value sufficient to enable energy to pass from the lower to the upper portion of the lens, around this plate. Plate 31, therefore, had a radius R_3 equal to 17.84", differing from R by 0.16". In this system, C differed from C_p by only 0.006 R or 0.01". This system had an f -number equal to 0.45, being faster than the concentric system shown in FIGS. 1 and 3 which had an f -number equal to 0.78. Both of these systems were capable of scanning angles in excess of 40 degrees to either side of their axes.

It should be understood that the embodiments of FIGS. 4 to 7 operate on exactly the same principles as those of FIGS. 1 to 3, all embodiments having a cross-sectional shape that is circularly symmetrical. Thus, the embodiments of FIGS. 4 to 7 could use spherical instead of cylindrical reflectors and lenses. Further, since the pillbox merely serves to direct the energy, the spherically concentric systems of FIGS. 1 to 3 could be used with equal success in pillbox antenna systems similar to those shown in FIGS. 4 to 7, and these pillbox systems could have either cylindrical or spherical lenses and reflectors.

It should also be understood that although the various embodiments of the invention have been shown as using feed horns or rotary switches to direct energy toward the reflector, any means of so directing energy could be used since the invention is not limited to any particular type of feed system. Further, it should be clear that the size of the dielectric correctors will vary in accordance with Formulas 1 to 8 in accordance with the material used and the type of lens desired. By use of these formulas, such changes and modifications as are necessary may be readily made.

While there have been described what are at present considered preferred embodiments of the invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention; and it is aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A rapid scan antenna system comprising: a double layer pillbox including top and bottom metallic plates that are respectively portions of a disk having a radius R , a middle plate that is a portion of a disk with a radius substantially less than R , and a reflector having a reflecting surface in the form of a portion of a cylinder of radius R and disposed about said top and bottom plates to serve as a boundary for such pillbox, said reflector having aberration of a given sign; a dielectric lens coaxial with said reflector and disposed partially between said top and middle plates and partially between said bottom and middle plates, the outer circumference of said lens having the form of a portion of a cylinder and being in close electrical contact with said reflector for introducing aberration opposite in sign to that of said reflector to correct the aberration thereof; and rotatable scanning means disposed adjacent to said pillbox substantially at a point along the axis of the reflector-lens combination

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corresponding to the focus thereof for directing microwave electromagnetic energy through said lens toward the reflecting surface of said reflector through a given angular sector, the ratio of the focal length of the reflector-lens combination to the effective aperture of said reflector being less than 1.

2. The system of claim 1, wherein the portion of said lens between said top and middle plates has the cross-sectional shape of a portion of an annulus with an inner radius R_1 and the portion of said lens between said bottom and middle plates has the cross-sectional shape of a portion of an annulus with an inner radius C_p , C_p being determined by

$$C_p = \frac{1}{2/R(n-1)/R_1}$$

and being the point along the axis of the reflector-lens combination where energy entering said combination at a height H above said axis and parallel thereto crosses said axis, n being the index of refraction of said lens, C_p being substantially equal to

$$C = \frac{\frac{H}{n}}{\sin \left[2 \sin^{-1} \left(\frac{H}{nR} \right) + a \right]}$$

where a is determined by

$$a = \sin^{-1} \left[\frac{H}{R_1} \right] - \sin^{-1} \left[\frac{H}{nR_1} \right]$$

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3. The system of claim 2, wherein $R_1 = 0.470 R$. H has a maximum value of $0.40 R$, and $n = 1.6$.

4. The system of claim 3, wherein $R = 18''$, said rotatable scanning means comprising a plurality of rotatable feed horns the mouths of which are disposed along a circle having a radius substantially equal to C_p , said feed horns respectively being receptive of microwave electromagnetic energy as each successively passes through said given angular sector and being disposed between said bottom and middle plates, and further including a pair of vanes respectively attached to said top and middle plates for directing the energy leaving said lens.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,071,768

January 1, 1963

Allen S. Dunbar

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 3, lines 31 to 34, equation 2, should appear as shown below instead of as in the patent:

$$\frac{1-n-1}{f \quad n} \left[\frac{1}{R_1} - \frac{1}{R_2} \right]$$

same column 3, lines 42 to 45, equation 3, should appear as shown below instead of as in the patent:

$$C = \frac{H}{\sin \left[2 \sin^{-1} \left(\frac{H}{R} \right) + a \right]}$$

column 4, lines 73 to 75, equation 5, should appear as shown below instead of as in the patent:

$$a = \sin^{-1} \left[\frac{H}{R_1} \right] - \sin^{-1} \left[\frac{H}{nR_1} \right]$$

Signed and sealed this 10th day of September 1963.

(SEAL)

Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of
Patents