This invention relates to antennas, and more particularly to an electronically operated rapid scan antenna.

The function of a scanning antenna is two-fold. First, it shapes the radiated energy into a pattern or beam to give the antenna directivity. Secondly, it rotates or scans this beam over a desired field of search. Heretofore, a scanning antenna has comprised a beam-shaping mechanism such as a paraboloid reflector, a dielectric or waveguide lens, or a planar array of antenna elements, together with means for mechanically rotating the entire structure. The principal disadvantage of such a system is the slow operation with which it can be rotated. Another technique consists of forming the beam by means of a planar array of elements, the phases of which are electronically related and controlled. This system permits rapid scanning of the beam but over a restricted scanning area and frequency band limitations.

A general object of our invention is the provision of an electronically controllable antenna capable of scanning at high speeds over an angle between 0° and 360°.

In accordance with our invention, a ring of ferromagnetic material, such as ferrite, is disposed concentrically of the feed point of a center-fed parallel plate antenna between the antenna plates. A magnet or series of magnets mounted adjacent to the ferrite ring externally of the antenna are energized in such a manner as to magnetize a sector of the ferrite ring differentially than the remainder of the ring so that microwave energy propagating through that sector is focused into a typical cigar-shaped beam. The portion of the ring in this condition is essentially a microwave lens. The beam is rotated about the antenna axis, that is, is scanned, by rotation of the magnetic field distribution by electronic control means. The non-lens sector of the ring preferably is magnetically biased to the ferromagnetic resonance region of the ferrite so that energy which does not pass through the lens sector is attenuated, thereby enhancing the front-to-back ratio of the antenna.

The invention will more readily be understood by reference to the accompanying drawings in which:

FIGURE 1 is a partially schematic side elevation of a parallel plate antenna embodying our invention.

FIGURE 2 is an enlarged transverse sectional view of the antenna taken on line 2—2 of FIGURE 1.

FIGURE 3 is a schematic plan view of the ferrite ring showing the lens sector as shaded and illustrating the focusing action of the lens.

FIGURE 4 is a curve showing the magnetic field distribution in the ferrite ring for shaping the beam and attenuating the back radiation.

FIGURE 5 is a schematic fragmentary plan view of the lens portion of the ring illustrating the changing phase front of the radiated energy.

FIGURE 6 is a typical radiation pattern of the antenna embodying the invention compared to the pattern (dotted) which would be obtained with no magnetic field.

FIGURE 7 is a schematic plan view of the antenna showing the power source and electronic control by which the series of magnets are sequentially energized for forming and rotating the radiated beam.

FIGURE 8 is an enlarged sectional view of the antenna taken on line 8—8 of FIGURE 7.

FIGURE 9 is a plot of coil current against field strength and against time showing the influence of the parameters for formation and rotation of the beam.

FIGURE 10 is a plan view, partially cut away, of a modified form of antenna utilizing dual concentric rings of ferrite; and

FIGURE 11 is a side elevation view partially in section and partially schematic of the antenna of FIGURE 10.

Referring now to the drawings, an embodiment of the invention is shown as a parallel plate antenna 5 having an axis A and comprising closely spaced (less than one-half wavelength) upper and lower plates 10 and 11 connected to a microwave transmission line 14 so that electromagnetic energy from the line propagates radially outwardly between the plates from the center point at axis A. The outer marginal portions of the inner plate surfaces diverge in the usual manner to appropriately alter the radiation in the plane orthogonal to the scanning plane. In a preferred form of the antenna, the plates 10 and 11 are circular.

In normal operation without a microwave lens, the parallel plate antenna radiates microwave energy equally in all directions in the plane of the plates so that the radiation pattern in this plane about the center of the antenna is essentially circular. In order to concentrate radiation in one direction from the antenna so that it has directivity, a ring 15 of ferromagnetic material, such as ferrite, is mounted between the antenna plates concentrically of the center feed point and is magnetized by an external magnetic circuit. This circuit is shown in FIGURE 2 in somewhat schematic form and comprises an annular electromagnet assembly 22 of a plurality of electromagnets each having a U-shaped (cross-section) core with inner and outer members 23 and 24 serving as poles, and an energizing coil 25. A similarly shaped annular core unit 26 mounted above upper antenna plate 10 has inner and outer ring members 27 and 28 aligned with the poles 23 and 24, respectively, of the several electromagnets so as to cause the magnetic field generated by the latter to traverse the gap between the plates in the direction of the arrows in FIGURE 3. FIGURE 2 shows the path of the magnetic field which exists between the inner pole 23 of each electromagnet core and the inside ring member 27 of the upper core and so is magnetized thereby. By controlling the strength of this field over a limited sector, the permeability of the affected sector of the ferrite ring, and thus its index of refraction, is varied to form the desired beam of radiant energy.

While a preferred embodiment of the invention contemplates a rotating magnetic field involving use of a series of separately energized electromagnets, a single ring-type magnet, either permanent or electromagnet types, may be employed together with means for mechanically rotating the antenna structure in order to angularly displace the beam. Such an arrangement would be useful in applications involving slow scanning rates. The field distribution necessary to properly form the beam could be obtained by controlling the contour of the pole face so as to vary the gap and the field strength. A pole face made of a series of adjustable slugs for changing the air gap with angle would be suitable for this purpose. The beam of energy is formed by reducing the biasing field strength over a limited sector of the ring as compared to the field applied to the remainder of the ring. This is illustrated schematically in FIGURES 3 and 4 wherein the unshaded portion 15a of the ring 15, see FIGURE 3, is magnetized to an average internal field strength of 1400 oersteds, see FIGURE 4, and the shaded portion 15b of the ring has a field of smaller magnitude.
The field gradient over the shaded portion 15b, called the lens sector of the ring, decreases from a maximum at the outer limits of the sector along the 50° and 60° radial lines, to a minimum of about 350 oersteds at the two degree zone. This field distribution is represented by the curve 38 in FIGURE 4.

This variation in applied field across the ferrite ring induces a corresponding variation in the permeability in the ferrite so that the index of refraction of the lens sector is controlled to give desired shaping of the beam. More specifically, the formation of a directive beam requires that rays 31, 32, 33, 34 and 35, see FIGURE 3, emanating from the center of the antenna and passing through the lens sector 15b shall be bent into parallelism and that the phases of these rays shall be substantially the same along the plane front indicated by the broken line 36. The phase-changing function, which causes ray bending, is accomplished by causing the index of refraction of lens sector 15b to vary in a prescribed manner as expressed as follows:

\[ n = n_0 + (1 - \cos \theta) \]

where \( n \) is the index of refraction, \( \theta \) is the angle, and \( n_0 \) is the index of refraction at the center of the lens where \( \theta = 0 \).

The relationship of index of refraction of the ferrite to its permeability is:

\[ n = \sqrt{n_e} \]

where \( n \) is the index of refraction, \( e \) is the dielectric constant of the ferrite, and \( n_e \) is the permeability of the ferrite, the latter being an inverse function of field strength. As field strength decreases, permeability increases and the index of refraction likewise increases. By controlling the field across sector 15b as shown by curve 38 in FIGURE 4, its permeability along the portion of the ferrite through which ray 33 passes is high and the index of refraction at that point is also high. Conversely, the permeability and index of refraction at those portions of the ferrite traversed by rays 31 and 35 are low. As a result, the phase of ray 33 is delayed with respect to the phases of rays 31 and 35 so that the three rays arrive at broken line 36 with equal phase fronts. Similarly, rays 32 and 34 are delayed and bent into parallelism with the above-mentioned rays so as to have an equal phase front. The total effect, therefore, of lens sector 15b is that of a microwave lens providing predetermined shaping of rays of energy radiating from the center feedpoint to give the radial antenna gain and directivity as suggested in FIGURE 6.

In forming a plane wavefront is further explained in FIGURE 5 showing three of the rays of energy, designated \( x, y \) and \( z \), passing through lens sector 15b of the ferrite ring. The broken line arc 1 and the inner surface 2 of the ring represent equal phase fronts of the radiant energy, that is, the phases of rays \( x, y \) and \( z \) at arc 1 are equal, and similarly they are equal at the intersection of the rays with surface 2. (The radii of arcs 1 and 2 being equal.) As the rays pass into the sector 15b, however, they are differently affected by the varied index of refraction of this part of the ferrite so that ray \( x \) travels further than ray \( y \) in the next increment of time, and similarly rays \( x \) and \( y \) travel further than ray \( z \). Thus the arc designated 3, representing the equal phase fronts of rays \( x, y \) and \( z \), has a larger radius than that of surface 2 or arc 1. As the rays continue through the ferrite, the equal phase front arc has an increasing radius until there is only a slight curvature within the ferrite along line 4 and a substantially plane front along line 5.

It should be noted that portion 15a of the ferrite ring is biased by a relatively high magnetic field preferably one having an intensity which produces a resonance condition in the ferrite. The rays of microwave energy propagating through this portion of the ring are substantially attenuated due to resonance absorption in the ferrite because of the low permeability and this reduces the effective radiation in the direction opposite from the beam. This result is clearly shown in FIGURE 6 wherein the solid line 35 designates the pattern resulting from use of the ferrite ring, and the dotted line 36 designates the antenna pattern without the ferrite ring. Note the radiation in the 180° direction is substantially reduced by the ferrite portion 15a. This results in a higher front-to-back ratio for the antenna with correspondingly improved performance.

Scanning of the beam 35 is accomplished by "scanning" the lens sector 15b electronically, that is, by progressively changing the biasing field around the ferrite ring so that the angular displacement of the depressed part of the field shown in FIGURE 4 is selectively varied. The control parameter is the current which energizes the several magnets of electromagnet assembly 22. By suitably controlling the current to all these biasing magnets, desired movement of the beam results. One system for so controlling the field is shown in FIGURES 7 and 8 wherein the separate electromagnets, designated \( m_1 \) through \( m_{12} \), are equally spaced around the antenna 5. Each of these magnets is energized by a steady biasing current from source 35 as applied to a coil \( p \) (not illustrated in FIGURE 7). Each magnet also has another coil \( p \) wound around its core. The several coils \( p \) are individually connected to separate phase control units \( c_1 \) through \( c_{12} \), which are connected to a source 40 of alternating current. The several phase control units, which may be artificial delay lines or dielectric materials having predetermined dielectric constants, serve to introduce a progressively increasing delay in the phase of the energizing currents so that the field produced by this current rotates about the antenna axis.

The steady biasing current from D.C. source 35 is of such magnitude that it produces a magnetic field of maximum intensity in the several magnets, such as the field in the ferrite of 1400 oersteds represented in FIGURE 4. The alternating current from source 40 effectively reduces the field produced by magnets associated with a limited portion of the ring to form the lens sector which shapes the beam. The other magnets produce full strength fields across the remainder of ferrite in response to the D.C. biasing current.

The relationship of bias and phasing currents and the fields they produce will be better understood by reference to FIGURE 9. Field strength of the magnet increases generally linearly with coil current, see FIGURE 9(a), up to the saturation point 42, beyond which a further increase in current produces no substantial change in field. The biasing current \( b_i \) exceeds the saturation current \( i_s \) by a predetermined amount \( \Delta i \). The alternating phasing current, indicated as a sine wave 45 in FIGURE 8(b), swings about the bias level as shown so as alternatively to add to and subtract from the bias current. The increase in total coil current above the \( i_s \) value does not change the field strength of the magnets but a decrease in current less than the saturation level does change the field proportionally. Therefore, the unshaded portion 46 under curve 48 alone is effective to produce a decrease in field strength which is a maximum during the rest of the cycle.

As a result of the differential \( \Delta i \) in bias and saturation current levels, the dip in field strength occurs during an interval which is less than half a period of the alternating current 45. This is shown in FIGURE 9(b) wherein coil current dips below saturation value during the time \( T_3 - T_2 \), less than the half period \( T_1 - T_4 \). The portion of the cycle during which the field is decreased may be varied by changing the bias current level. By way of example, in order to produce a field decrease over a 120° sector as shown in FIGURES 3 and 4, the bias level is adjusted until \( T_3 - T_2 \) is equal to one-third of a period of the alternating phasing current.
The circuits described above and illustrated in FIGURES 7, 8 and 9 provide for a full 360° sweep of the beam of energy by rotating the magnetic field fully around the ferrite. It may be desirable to sweep the beam across a sector of less than 360° in order to scan a limited area, and in such cases any suitable electronic means may be employed for reversing the direction of rotation of the field at the opposite limits of the scanned sector.

An antenna which was actually constructed in accordance with this invention and which was successfully operated and tested, has the following characteristic and dimensions:

**General:**
- **Frequency:** 10 kilomegacycles.
- **Feed:** Coaxial.

**Ring:**
- **Thickness (plate gap):** ¼ inch.
- **Outside diameter:** 6 inches.
- **Inside diameter:** 4 inches.

**Material:** Manganese magnesium ferrite.

**Applied magnetic field:**
- **Maximum:** 3000 gauss.
- **Minimum:** 350 gauss.

**Increase in gain relative to omni-directorial antenna:** 10 decibels.

**Beamwidth:** 13 degrees.

**Front-to-back ratio:** 25 decibels.

In the testing of the above antenna, it was determined that gain increased and beamwidth decreased as the outside diameter of the ferrite ring was increased, in accordance with the following relationship:

$$\Delta G = \frac{4b}{\lambda} \sin \theta_m$$

where $\Delta G$ is the increase in gain, $b$ is the outer radius of the ring, $\theta_m$ is the half lens sector, and $\lambda$ is the operating wavelength.

A modified form of the invention is shown in FIGURES 10 and 11 as a parallel plate antenna 59 similar to antenna 5 described above except that a pair of concentric ferrite rings 51 and 52 are used instead of one such ring. Since the antenna 50 is the same as antenna 5 in other respects, like reference characters indicate like parts in the drawings. The two rings 51 and 52 are located in the gaps defined by the poles 23 and 24 of the several electromagnetic and the ring members 27 and 28, respectively, of upper core unit 26. Rings 54, 55, and 56 of dielectric material radially adjacent to the ferrite rings match the latter to the propagating microwave waves. If more precise control of the field applied to the separate rings is desired, two sets of bias and phasing coils may be used, one set being located on each leg of the respective magnets adjacent to the ring. By using two ferrite rings there is a reduction in the coil current required to produce a given applied magnetic field since the air gap in the magnetic field line is reduced considerably. Also the ray bending necessary for each ferrite ring is shared so that field applied to each ferrite ring is less than the single ring method. In addition, more directivity and gain results with same size antenna since outer ferrite ring determines effective antenna aperture which is larger than single ring case.

Modifications and changes may be made to the above-described embodiments of our invention without departing from the precepts thereof, and accordingly the appended claims define whatever features of patentable novelty reside in the invention.

We claim:

1. An antenna comprising two parallel plates spaced apart transversely of the planes of the plates, a transmission line connected to one of the plates for transmitting electromagnetic waves to and from the space between said plates, an annulus of ferromagnetic material disposed between said plates concentrically of said transmission line with the plane of the annulus substantially parallel to the planes of the plates, and an annular series of electromagnets disposed adjacent to the exterior of one of said plates, each electromagnet having electric coil means and a pole piece transversely aligned with said ferromagnetic annulus for halving for producing a magnetizing field in a alternating current connected to the coil means of said electromagnets, a source of direct current connected to said coil means, the current from said direct current source being of such magnitude that the entire ferromagnetic annulus is magnetized to saturation level, the current from said alternating current source being of such magnitude as to decrease the magnetization of a sector of the annulus whereby electromagnetic waves propagating through the sector are formed into a directive beam, and phase control means connected between said alternating current source and said coil means and progressively delaying the phase of the alternating current applied to the several coil means whereby said sector of decreased magnetization is progressively shifted over said ferromagnetic annulus to rotate the beam.

2. The antenna according to claim 1 in which the coil means on each electromagnet comprises a biasing coil and a phasing coil, said direct current source being connected to said biasing coil and said phase control means being connected to said phasing coil.

3. The antenna according to claim 2 comprising a second annulus of ferromagnetic material disposed concentrically of the first named annulus, each of said electromagnets having a second pole piece transversely aligned with said second annulus.

4. An antenna comprising two parallel plates spaced apart transversely of the planes of the plates, a transmission line connected to one of the plates for transmitting electromagnetic waves to and from the space between said plates, an annulus of ferromagnetic material disposed between said plates concentrically of said transmission line with the plane of the annulus substantially parallel to the planes of the plates, and an annular series of electromagnets disposed adjacent to the exterior of one of said plates, each electromagnet having electric coil means and a pole piece transversely aligned with said ferromagnetic annulus for magnetizing same, a source of energizing current for said coil means, and control means connected to said coil means for producing a magnetizing field in a sector of said ferromagnetic annulus adapted to the electromagnetic waves propagating therethrough into a beam.

5. An antenna comprising two parallel plates spaced apart transversely of the planes of the plates, a transmission line connected to one of the plates for transmitting electromagnetic waves to and from the space between said plates, an annulus of ferromagnetic material disposed between said plates concentrically of said transmission line with the plane of the annulus substantially parallel to the planes of the plates, electromagnet means disposed adjacent to the exterior of one of said plates and adapted to produce a magnetic field through said ferromagnetic material, a source of energizing current for said electromagnet means, and control means for controlling said energizing current whereby said electromagnet means produces a non-uniform field in said annulus for forming said waves into a beam.

6. An antenna comprising two parallel plates spaced apart transversely of the planes of the plates, means for feeding electromagnetic waves to the space between said plates, a ferrite annulus disposed between said plates concentrically of said feed means with the plane of the annulus substantially parallel to the planes of the plates, a series of electromagnets disposed adjacent to the exterior of said plates and adapted to produce a magnetic field through said annulus, a source of energizing current for said electromagnet means, and means for controlling the magnitude of the magnetic field produced by said...
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7. An antenna comprising two parallel plates spaced apart transversely of the planes of the plates, a center feed comprising a transmission line connected to one of the plates for transmitting electromagnetic waves to and from the space between said plates, a ferrite annulus disposed between said plates concentrically of said transmission line with the plane of the annulus substantially parallel to the planes of the plates, an annular series of electromagnets disposed adjacent to the exterior of one of said plates, each electromagnet having a core with separate biasing and phasing coils wound thereon, said core also having a pole piece transversely aligned with said annulus for magnetizing same, a source of direct current connected to said biasing coil, the magnitude of the output of said direct current source being such as to magnetize the ferrite annulus to saturation, a source of alternating current, phase control means connecting said alternating current source to said phasing coils for progressively delaying the phase of the current applied to the several coils means whereby the magnetic field produced in the annulus by the alternating current source rotates about the center feed, said biasing and phasing coils being arranged so that the magnetizing field across a limited sector of the annulus is less than the field across the remainder of the annulus, whereby electromagnetic waves propagating through said sector are formed into a directional beam and waves propagating through said remainder of the annulus are attenuated.

8. An antenna comprising two parallel spaced plates having a microwave feed point, an annulus of ferrite between said plates located concentrically of said feed point with the plane of the annulus substantially parallel to the planes of the plates, means for producing a magnetic field in said annulus whereby microwaves propagating through the annulus are formed into a directional beam, and means changing the position of said magnetic field relative to said annulus whereby to correspondingly shift the microwave beam.

References Cited by the Examiner

UNITED STATES PATENTS

2,869,124 1/1959 Marie 343—783
2,875,439 2/1959 Berkowitz.
2,939,141 5/1960 Casabona et al. 343—783 X
2,973,516 2/1961 Medved 343—787 X

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