Jan. 9, 1962 W. H. HEWITT, JR 3,016,535

SLOTTED WAVEGUIDE ANTENNA

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FIG. 1

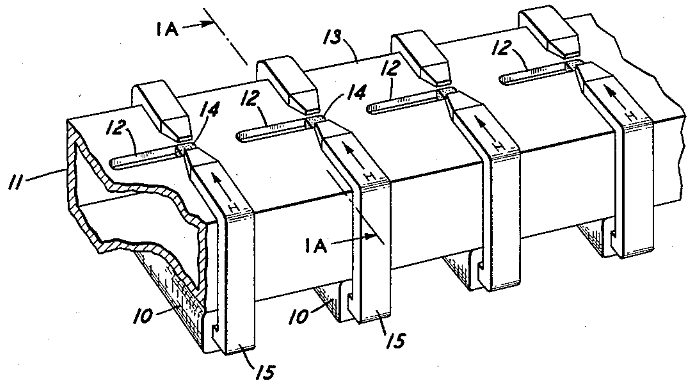

FIG. 1A

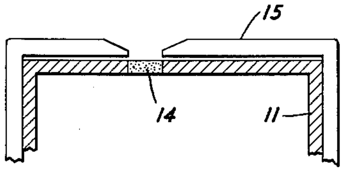

FIG. 2

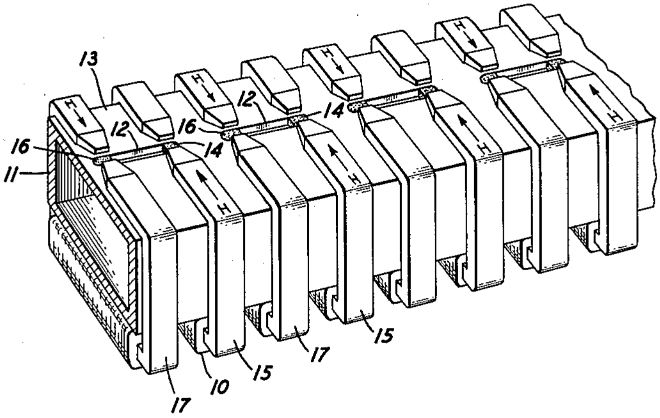

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FIG. 3

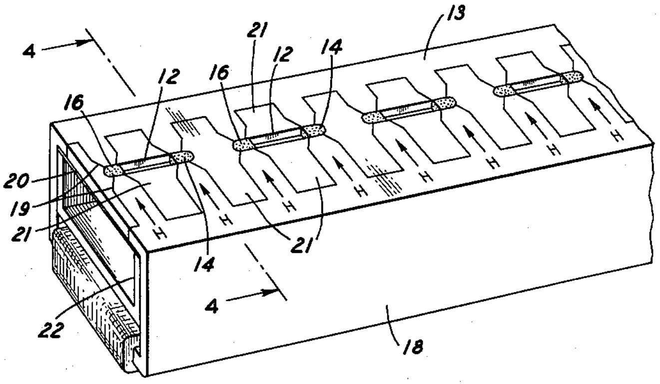

FIG. 4

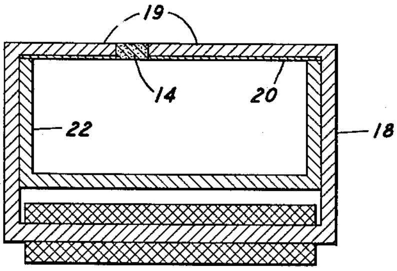

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FIG. 5

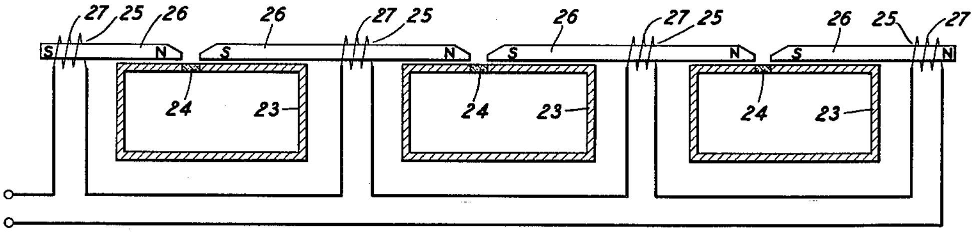


FIG. 6

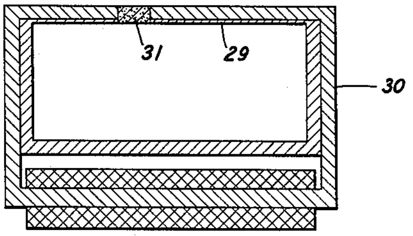
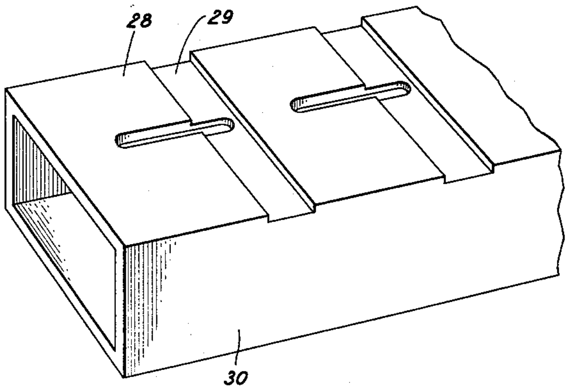


FIG. 7



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SLOTTED WAVEGUIDE ANTENNA

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This invention relates to directive antennas, and more particularly to such antennas of the slotted waveguide type.

A slotted waveguide antenna may be readily designed to give any one of a number of radiation patterns. The particular pattern radiated may be arrived at through control of the conductivity of the slots which in general are disposed in a predetermined longitudinal series. If the slots are highly conductive the amount of energy radiated from the first slot will be great and will diminish progressively with each succeeding slot. With selected high conductivity for each slot, a cosecant-squared pattern can be produced. Alternatively, if the slots are only slightly conductive, a small and uniform amount of energy will be radiated from each slot in the series, with a resulting pencil-beam pattern.

The cosecant-squared pattern is a familiar one and is used not only in airborne navigation radar but also in surface-based radar for the detection of airplanes. The pencil-beam pattern finds use in most all search radars.

In some instances, e.g., airborne navigational radar, it is desirable to change the radiation pattern of the antenna array from one pattern to another, for example, from a pencil-beam to a cosecant-squared and back again. To this end there has been proposed a slotted waveguide antenna wherein a collinear array of longitudinally extending slots are moved transversely of the longitudinal center line of the broad face of the guide. This is accomplished by forming the broad face of a separate plate, containing slots, and moving it transversely with respect to the rest of the guide. Increased transverse displacement from the center line of the guide increases the conductance of the slots and at some selected distance from said center line, determined of course by the frequency of the propagated energy, slot size, et cetera, the desired cosecant-squared pattern is obtained. For transverse slot locations near the center of the waveguide, pencil-beams result.

This mechanical method of changing from one radiation pattern to another is not entirely satisfactory. First, there is the problem of energy leakage or loss between the moving parts. There is always present the inherent inaccuracies in mechanical arrangements due to backlash and the like. And, in general, the arrangement has been found cumbersome and difficult to readily mount on aircraft.

It is the object of this invention to electrically control the radiation pattern emanating from a slotted waveguide antenna.

A related object is to electrically switch from one pattern of radiation to another using a single antenna array.

In addition to transversely displacing the slots, the conductance of the same can be controlled by choice of slot length. As shown by the curves on page 84 of the book by W. H. Watson, entitled "Waveguide Transmission and Antenna Systems" (1947), for any one transverse position of the slots the conductance (G) of each slot varies with slot length. A six percent decrease in slot length reduces the slot conductance by approximately half. Extending the curve (FIG. 34*d*) suggests that approximately a ten percent decrease in slot length will decrease the conductance to a value approaching zero. This effect can be briefly explained by considering the slots as resonant structures, and since conductance is a maximum for a resonant slot, any change in slot length will depart from resonance and thus decrease conductivity.

In accordance with the present invention the shape of the radiation pattern emanating from a slotted waveguide is controlled by effectively varying the length of each slot. The slots are uniformly loaded with one or more elements of gyromagnetic material and a variable magnetic biasing field is applied uniformly to the gyromagnetic elements of each slot. The magnitude and polarity of the field applied to each element determines its permeability and this affects the apparent or effective length of the slot which in turn, as previously mentioned, controls slot conductance. With the slot lengths, and thus their conductance, varied uniformly the slotted waveguide array may be switched to produce a cosecant-squared pattern (high slot conductivity) or a pencil-beam pattern (low slot conductivity).

The invention will be more fully apprehended by reference to the following detailed description of preferred illustrative embodiments thereof taken in connection with the appended drawings, in which:

FIG. 1 is a perspective view of a section of a waveguide having collinear slots formed in the broad face thereof with a magnetically polarized element of gyromagnetic material mounted in each slot;

FIG. 1A is a fragmentary side elevational view taken on the line 1A—1A of FIG. 1;

FIG. 2 is a view of a section of waveguide similar to FIG. 1 with a pair of magnetically polarized elements of gyromagnetic material mounted in each slot;

FIG. 3 is a perspective view of a section of a slotted waveguide wherein the core of the electromagnet comprises the broad face of the waveguide;

FIG. 4 is a view taken on the line 4—4 of FIG. 3;

FIG. 5 is a schematic diagram showing parallel arrays of slotted waveguides constructed in accordance with the present invention;

FIG. 6 is a cross sectional view of a modification of the invention wherein a portion of the thickness of the broad face of the waveguide is milled away; and

FIG. 7 is a perspective view of a section of the waveguide of FIG. 6.

Referring now to the drawings, FIG. 1 shows a section of waveguide **11** having collinear spaced slots **12** formed in the broad face **13**. The slots, which may be approximately twenty or more in number, extend longitudinally along the waveguide **11** and are transversely displaced a predetermined distance from the longitudinal center line of the broad face of the guide. As is well known in the waveguide art, each aperture or slot constitutes a point source of radiation and by reason of constructive and destructive interference which takes place between the rays from the several apertures, the row of apertures taken together radiate energy in a complicated pattern. As indicated above, the particular pattern radiated may be arrived at through control of the conductivity of each slot, and this in turn can be effected in one manner by transversely displacing the slots from the longitudinal center line of the broad face **13**. With a 2 decibel radiation loss for each slot, an approximation of a cosecant-squared pattern results. With the radiation loss for each slot reduced to 0.3 decibel or less a pencil-beam pattern results.

An element of gyromagnetic material **14**, such as ferrite, is placed in each slot at a position adjacent one of the ends thereof. The electromagnets **15** provide the necessary transverse magnetic fields for the ferrites. The coils **10** of the electromagnets **15** may be connected either in series or parallel, and through provision of a current control means (not shown) the magnetic fields applied to the ferrites may be varied in amplitude and polarity.

The term "gyromagnetic material" is intended to include any of the number of ferromagnetic materials which comprise an iron oxide in combination with one or more bivalent metals, such as nickel, magnesium, zinc, manganese and the like. These materials combine with the iron oxide in a spinel structure and are known as ferromagnetic spinels or as polycrystalline ferrites. The materials possess magnetic properties of the type disclosed in the article by D. Polder which appeared in volume 40, pages 99 through 115 of the January, 1949, Philosophical Magazine.

While the ferrite elements **14** are preferably placed at either of the ends of the elongated slots so as to reduce reflections, this is not essential and the desired results can be achieved with the ferrites spaced at some intermediate position from either of the ends. From FIGS. 1 and 1A it will be seen that the pole pieces of the electromagnets **15** are tapered in elevation and in plan. This is done primarily to insure a concentration of the magnetic fields in the ferrites. However, as will be seen from FIG. 1A, the elevation taper further serves to reduce the possibility of the pole pieces presenting any obstruction to the energy being propagated. It would appear from FIG. 1A that the magnetic fields might travel through the air from pole to pole, but it must be remembered that the direct current permeability of gyromagnetic material is much greater than air, and thus substantially all the field is applied thereto.

In the copending application of S. E. Miller, Serial No. 362,193, filed June 17, 1953, now Patent No. 2,951,220, it was shown that a transversely applied magnetic field has the effect of increasing or decreasing the radio frequency permeability of a ferrite disposed in a waveguide. Whether this permeability is increased or decreased and the extent thereof depends upon the transverse position of the ferrite in the waveguide and the direction and magnitude of the applied field. An increased permeability has the effect of increasing the apparent or effective length of the transverse dimension of the rectangular waveguide. In like manner, a decreased permeability decreases the effective transverse dimension.

Considering now the slotted waveguide of the present invention, each slot can be thought of as a small rectangular waveguide, the slot length being equivalent to the wide dimension of the waveguide and the narrow ends the equivalent of the narrow walls. Thus, the ferrite in each slot behaves in a manner similar to a ferrite in a waveguide, serving to increase or decrease slot length when magnetically polarized. The electrical field in the slot is perpendicular to the slot length.

With a ferrite positioned in each slot as shown in FIG. 1, a magnetic field applied in the direction indicated by the arrow will have the effect of decreasing the permeability of the ferrite and thus of shortening the slot. A field applied in the opposite direction, of course, increases permeability and thus slot length. And, if the ferrite was positioned adjacent the opposite end, a field applied in the direction indicated would increase slot length.

In the embodiment of FIG. 1, assume that the magnetic field is zero and the effective length of each loaded slot is such that the conductance or radiation loss for each is 2 decibels, i.e., the slots are close to resonance for the frequency being propagated. Now by applying a uniform magnetic field to each ferrite of approximately 2,000 oersteds in the direction shown, the slot length will be reduced and the conductance of each slot will diminish to a value under 0.3 decibel, the effect of this being that the radiation pattern is switched from a cosecant-squared to a pencil-beam. The same result can be achieved by applying the magnetic field in the opposite direction. In this latter case, the slot length will, of course, be increased but the effect on slot conductance is the same.

Alternatively, with a magnetic field of zero and the effective slot length sufficiently greater than that for resonance as to result in low conductivity (pencil-beam pattern), a magnetic field of approximately 2,000 oersteds, applied in the direction shown, will result in the effective slot length approaching that for the resonant condition and thus high slot conductivity is achieved (cosecant-squared pattern).

The modification of FIG. 2 is similar to that of FIG. 1 except that a second element of gyromagnetic material **16** is placed in each slot adjacent the other end thereof. The electromagnets **17** provide the transverse magnetic fields for these second ferrite elements. Since each element **16** is on the side of the slot opposite from element **14**, the magnetic field applied thereto should normally be the reverse of that applied to element **14**. Thus, with the respective fields applied in the indicated directions, each element of gyromagnetic material when magnetized will effect a reduction in slot length. If the fields are reversed in direction, each element will effect an increase in slot length. The obvious advantage of this arrangement is that even greater variations in slot length may be obtained inasmuch as both gyromagnetically polarized elements assist in producing the desired result. The operation of this second embodiment follows that of FIG. 1.

In the modifications of FIGS. 1 and 2, if the ferrite elements are magnetically polarized so as to present a permeability of less than one to the energy being propagated, then a permeability of greater than one is presented to energy returning in the opposite direction. Thus, the return energy will see a different slot length, and slot conductance, than that presented to the propagated energy. If it is desired to maintain the same slot length for both the transmitted and returned energy, an arrangement such as that shown in FIG. 3 may be used.

In FIG. 3, the elements **14** and **16**, mounted in each slot, are magnetically polarized in the same direction as shown by the arrows. Thus, while the magnetically polarized element **14** presents a permeability of less than one to the propagated energy, the element **16** presents a permeability greater than one. The tendency is for the effect of one ferrite element to offset the other. However, as will be evident from the Miller application noted above, for the same magnitude of applied field the effect of ferrite element **14** (decreased permeability) is substantially greater than the effect of element **16**, and thus switching between radiation patterns can still be carried out.

As indicated, the principal advantage of this latter embodiment is that the same slot length is presented irrespective of the direction of travel of the energy; that is, the arrangement is reciprocal. For the return direction, of course, the respective elements produce the opposite effects (element **14** presents increased permeability and element **16** decreased permeability), but the overall total effect is the same. That is, the permeability of ferrite **14** for the forward direction is equivalent to the permeability of ferrite **16** for the reverse direction and vice versa, assuming no magnetic field changes.

In the FIG. 3 embodiment, the electromagnet **18** comprises a single core having multiple pole pieces **19**. The electromagnet supplies the magnetic fields for all the ferrite elements and necessarily all the fields are applied in the same direction. Close fitting brass inserts **21** are placed between adjacent pole pieces. As shown more clearly in FIG. 4, the upper broad face of the waveguide **22** has been removed. The pole pieces **19** of the electromagnet and the brass inserts **21** form the broad face of the guide, and the pole pieces and inserts are so shaped as to define the slots therebetween. The ferrites **14** and **16** are placed between the pole pieces **19**, and thus a more direct application of the fields to the ferrites is achieved. The under-surface of the pole pieces and the brass inserts are plated with gold **20**, following their assembly, to prevent any energy loss between mating surfaces.

In many instances it is desirable to have a radiation pattern which is as narrow as possible in one direction but spread out in the other. For example, the cosecant-squared pattern should possess a cosecant-squared configuration in the vertical or elevational direction and yet be very narrow in the horizontal or azimuthal direction. To this end a number of slotted waveguides **23** are placed parallel and adjacent each other as shown in FIG. 5. Transverse magnetization for the ferrites **24** in each waveguide is provided by electromagnets **25** which comprise elongated, bar-like cores **26** and coils **27**. The coils **27** are connected in series and when energized they set up magnetic fields having the polarity shown. Thus, all the ferrites are magnetically polarized in the same direction and a very narrow azimuthal pattern results.

In the modification of FIGS. 6 and 7, rather than remove all of the upper broad face of the waveguide, that portion most adjacent each ferrite is partially removed. For example, for the arrangement wherein a ferrite is to be placed in only one of the ends of each slot, the waveguide face **28** is milled away as shown at **29**. The face may be reduced to a thickness of approximately 0.005–0.010 inch. The electromagnet **30** is seated in the milled away portion and the ferrite **31** is placed between the pole pieces thereof. Thus, the field between the pole pieces is more directly applied to the ferrite and the possibility of the pole pieces obstructing the propagation of energy is eliminated.

If a predetermined pattern is achieved, any change in frequency may affect the pattern inasmuch as such a change will alter the conductance of each slot. To correct for this, a slotted waveguide antenna employing ferrites may be made frequency sensitive, i.e., the magnetic bias applied to the ferrites can be controlled in accordance with an error voltage derived from a frequency discriminator.

The foregoing description proceeded on the basis of switching between a cosecant-squared pattern and a pencil-beam. However, it will be clear to those in the art that switching may be obtained between any other two or more desired radiation patterns. And, for other patterns the fields applied to the ferrites would not necessarily be the same. That is, the conductance of successive slots in a waveguide may differ in some predetermined manner. Further, it is not necessary that the array of slots be collinear; other slot arrangements are well known in the art.

Accordingly, it is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A slotted waveguide antenna comprising a rectangular waveguide formed with a series of rectangular shaped slots spaced apart along the length of said waveguide for radiating into free-space the energy waves guided by said waveguide, said slots being located at predetermined positions in one of the broad faces of said waveguide and transversely displaced with respect to the longitudinal center line thereof, an element of gyromagnetic material uniformly disposed in each of said slots proximate to one of the ends thereof, and means for applying a variable biasing magnetic field to the gyromagnetic material in each of said slots to effectively alter the length of each slot, said biasing magnetic field being applied in a direction transverse to the direction of travel of the energy through each slot.

2. In a directive antenna array wherein the energy emanating therefrom is electrically switched from one pattern of radiation to another, a rectangular waveguide formed with a series of collinear elongated slots in one of the broad faces thereof, each of said slots being uniformly loaded with at least one element of gyromagnetic material asymmetrically disposed therein, the loaded slots being spaced at predetermined positions along the length of said waveguide for radiating into free-space a selected amount of the energy of the waves being guided along

said waveguide, and means for uniformly applying a predetermined transverse biasing magnetic field to each of the gyromagnetic elements in said slots to effectively alter the length of each slot so that the amount of energy radiated by each slot is changed to a second selected amount.

3. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a collinear series of longitudinally extending rectangular slots spaced apart along the length of said waveguide for radiating into free-space the energy of waves guided by said waveguide, said slots being located in predetermined positions in one of the broad faces of said waveguide and transversely displaced with respect to the longitudinal center line thereof, gyromagnetic material asymmetrically disposed in the same location in each of said slots, and means for applying a variable biasing magnetic field to the gyromagnetic material in each of said slots to effectively vary the length of each slot, the gyromagnetic material in all of said slots being magnetically biased in the same direction transverse to the direction of travel of energy through the slots.

4. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a series of collinear slots in one of the broad faces thereof, said slots being spaced apart along the length of the waveguide and transversely displaced with respect to the longitudinal center line of the broad face thereof, said slots being of substantially greater length than width, an element of gyromagnetic material uniformly disposed in each of said slots adjacent one of the ends thereof, and means for uniformly applying a variable biasing magnetic field to each of the elements in a direction transverse to the length of the slots.

5. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a series of slots spaced apart along the length of said waveguide for radiating outward therefrom the energy of waves guided by said waveguide, a pair of elements of gyromagnetic material uniformly disposed in each of said slots on opposite sides thereof, and means for applying a variable biasing magnetic field to the gyromagnetic elements in each of said slots, the gyromagnetic elements of each slot being magnetically biased in the same transverse manner as the gyromagnetic elements of the other slots.

6. Apparatus as defined in claim 5 wherein the gyromagnetic elements in each slot are magnetically biased in opposite transverse directions.

7. Apparatus as defined in claim 5 wherein the gyromagnetic elements in each slot are magnetically biased in the same transverse direction and to the same extent.

8. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a series of collinear slots in one of the broad faces thereof, said slots being spaced apart along the length of the waveguide and transversely displaced with respect to the longitudinal center line of the broad face thereof, said slots being substantially greater in length than width, a pair of elements of gyromagnetic material uniformly disposed in each slot at the opposite ends thereof, and means for applying a variable biasing magnetic field to the gyromagnetic elements in each of said slots, the gyromagnetic elements of each slot being magnetically biased in the same manner and to the same extent as the gyromagnetic elements of the other slots.

9. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a series of slots in one of the broad faces thereof, said slots being spaced apart along the length of said wave-

guide for radiating outward therefrom the energy of waves guided by said waveguide, gyromagnetic material located in each of said slots, the slotted broad face of said waveguide having transversely milled portions of substantially reduced thickness in the vicinity of the gyromagnetic material in each slot, and electromagnetic means for applying a variable biasing magnetic field to the gyromagnetic material in each of said slots, said electromagnetic means having pole pieces which are seated in said transversely milled portions with said gyromagnetic material disposed between opposed pole pieces.

10. In a directive antenna array wherein the pattern of radiation of the energy emanating therefrom is electrically controlled, a rectangular waveguide formed with a series of slots in one of the broad faces thereof, said slots being spaced apart along the length of said waveguide for radiating outward therefrom the energy of waves guided by said waveguide, an electromagnet having a plurality of parallel pairs of opposed pole pieces, close-fitting non-magnetic inserts disposed between adjacent parallel pole pieces, said pole pieces and non-magnetic inserts forming the aforementioned broad face of the waveguide and defining said slots therebetween, and gyromagnetic material disposed in each of said slots and between opposed pole pieces.

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