Feb. 5, 1963 **W. H. HEWITT, JR** **3,076,946**

NONRECIPROCAL RECTANGULAR WAVE GUIDE DEVICE

Filed June 17, 1953

2 Sheets-Sheet 1

FIG. 1

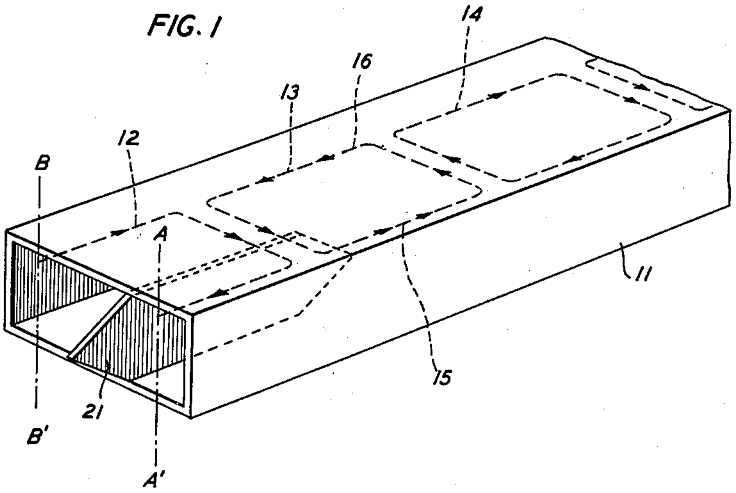


FIG. 2

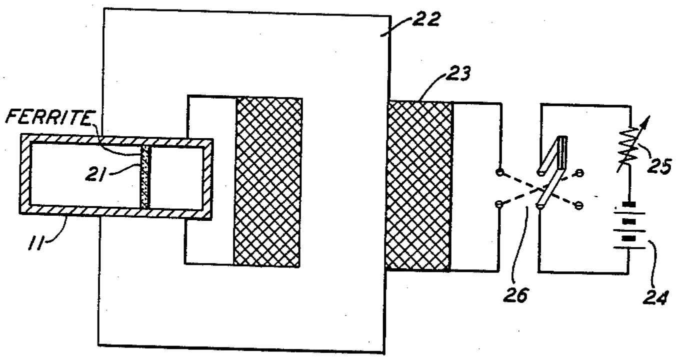
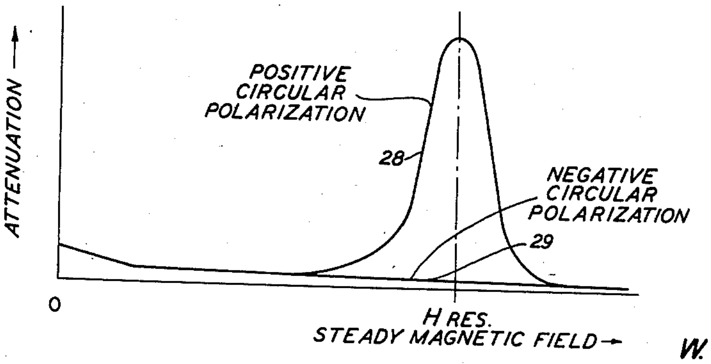


FIG. 3



INVENTOR
W. H. HEWITT, JR.
BY Hugh S. Wertz
ATTORNEY

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FIG. 4

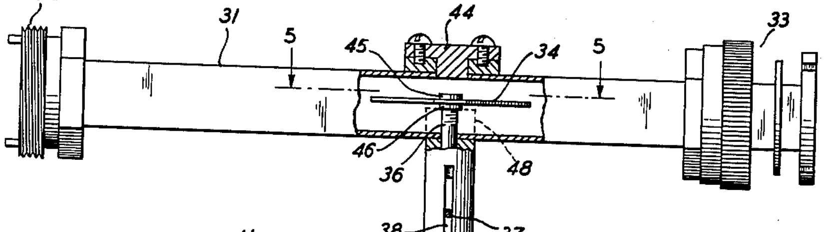


FIG. 8

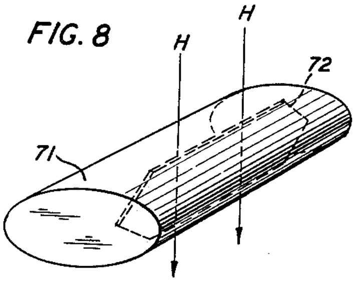


FIG. 5

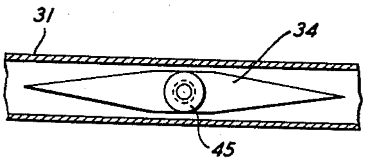


FIG. 7

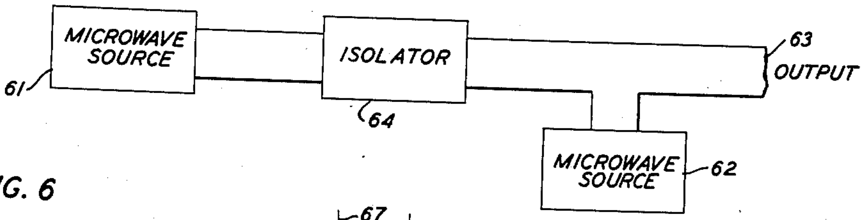
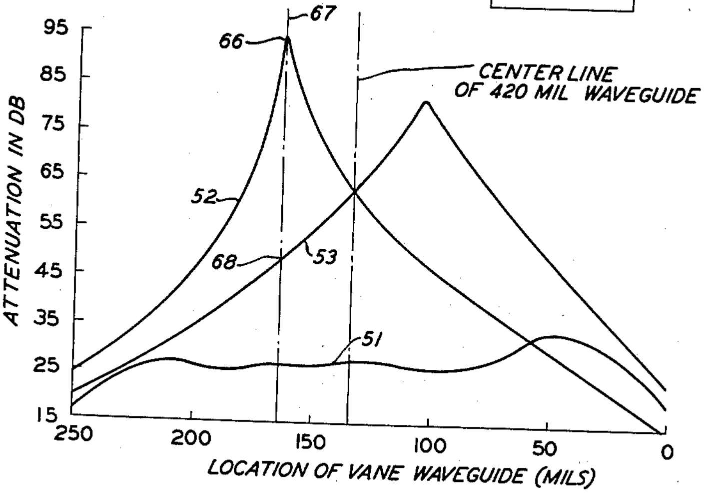


FIG. 6



INVENTOR
W. H. HEWITT, JR.
BY Hugh S. Wertz
ATTORNEY

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NONRECIPROCAL RECTANGULAR WAVE GUIDE DEVICE

William H. Hewitt, Jr., Mendham, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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6 Claims. (Cl. 333—24.2)

This invention relates to very high frequency and microwave components, and more specifically to passive devices which have different transmission characteristics for opposite directions of transmission.

As developed in C. L. Hogan's article entitled "The Microwave Gyrator" which appeared in volume 31, pages 1 through 31 of the January 1952 Bell System Technical Journal, passive non-reciprocal microwave components can be obtained by the use of ferrite cylinders having an axial magnetic field in a circular wave guide. The gyrator structure disclosed in this article, however, is a moderately complex structure, requiring transition elements for changing from rectangular to circular wave guide and vice versa, resistive vanes for suppressing unwanted reflected energy and tapered impedance matching elements for the ferrite cylinder, for example.

Accordingly, a principal object of the present invention is to simplify non-reciprocal microwave components.

A further object is to provide means for obtaining non-reciprocal effects in wave guides of rectangular cross-section.

A still further object is to obtain non-reciprocal effects in wave guides with a minimum of gyromagnetic material, the material being so positioned in the guide as to produce the desired result most effectively.

In accordance with the invention it is disclosed that an electromagnetic wave guiding structure having a polarized element of gyromagnetic material located asymmetrically with respect to the electromagnetic field within the wave guiding structure has a different transfer impedance for one relative orientation of the radio frequency and polarizing magnetic fields than for the opposite relative orientation. In one specific embodiment illustrated in the drawings, by way of example, a transversely magnetized septum of ferrite located off-center in a rectangular wave guide is found to produce substantially greater attenuation with the polarizing magnetic field in one direction than when the polarizing field is reversed.

Other features, objects and advantages of the invention will become apparent during the course of the following detailed description of the specific illustrative embodiments of the invention shown in the accompanying drawings.

In the drawings:

FIG. 1 indicates the pattern of radio frequency magnetic loops of a TE_{10} dominant mode wave in a rectangular wave guide having a septum of ferrite located therein;

FIG. 2 shows a cross-sectional view of a polarized septum of ferrite located asymmetrically in a rectangular wave guide;

FIG. 3 is a plot showing two attenuation characteristics illustrating the difference in attenuation when the septum of ferrite is located in a portion of the wave guide in which positively or negatively circularly polarized magnetic waves are present, respectively;

FIGS. 4 and 5 are various views of a wave guide section similar to that of FIG. 2 wherein the septum of gyromagnetic material is movable transversely in the guide;

FIG. 6 shows a pair of plots of attenuation versus septum position for the device of FIGS. 4 and 5 with oppositely polarized biasing magnetic fields, respectively;

FIG. 7 is a block diagram of a simple microwave system in which the isolator of FIG. 2 is employed; and

FIG. 8 illustrates the principles of the invention as applied to a dielectric wave guiding structure.

FIG. 1 indicates, by way of example and for purposes of illustration, the magnetic field configuration at a particular instant of a traveling electromagnetic wave of the TE_{10} dominant mode being propagated from left to right in rectangular wave guide section **11**. The lines of magnetic intensity are indicated by the loops **12**, **13**, **14**, and lie entirely in planes which are parallel to the wide dimension of the wave guide. As is well known to those skilled in the art, at points on vertical lines such as A—A′ and B—B′, between the center line of the wave guide and either side wall, the magnetic field will have both longitudinal and transverse magnetic field components. The field at these locations may therefore be said to be circularly or elliptically polarized, the direction of circular polarization being predominantly clockwise on one side (the near side) of the center line and counterclockwise on the other side. This clockwise and counterclockwise polarization may be appreciated, for example, by considering the direction of the lines of magnetic intensity at the fixed points **15** and **16** within the wave guide section **11** as the magnetic loops **12**, **13** and **14** move along the guide from left to right. For a more complete discussion of the propagation of the dominant mode TE_{10} wave in a rectangular wave guide, see "Principles and Applications of Waveguide Transmission," by Dr. G. C. Southworth, published by D. Van Nostrand Company, Inc., New York, 1950, with particular reference to Section 5.2 starting at page 102 and FIG. 5.2–1 on page 103. The tapered septum **21** of paramagnetic material in the wave guide **11** will be discussed in greater detail in conjunction with FIG. 2.

FIG. 2 shows a cross-sectional view of the wave guide **11** and a polarized vertically transverse septum of ferrite **21**. The polarizing field is applied to the septum **21** by an electromagnet comprising the core **22** of magnetic material and the coil **23** when the coil **23** is energized by power from a suitable electrical source **24** of direct current. A variable resistance **25** and the double pole double throw switch **26** provide for adjusting the strength of the magnetizing field and for reversing the same, respectively.

As indicated by D. Polder, Philosophic Magazine, volume 40, pages 99 through 115, January 1949, the permeability of an extended ferrite medium for an electromagnetic wave whose magnetic intensity is at right angles to a steady biasing magnetic field is substantially different for oppositely circularly polarized components of the magnetic intensity of the wave. One physical explanation which has been advanced to explain this phenomenon involves the assumption that the ferromagnetic material contains unpaired electron spins which tend to line up with the applied magnetic field. These electron spins and their associated moments can be made to precess about the line of the magnetic field, keeping an essentially constant component of magnetic moment in the biasing magnetic field direction but providing a magnetic moment which may rotate in a plane normal to this steady magnetic field direction. These magnetic moments have a tendency to precess in one angular sense, bu strongly resist rotation in the opposite sense. This tendency of a spinning element to consistently precess in one angular direction to the exclusion of the other is familiar to anyone who has watched a top wobble before stopping. Considering the interaction between the oppositely polarized components of high frequency magnetic intensity and the magnetic moments, it is clear that one of the circularly polarized components will be rotating in the easy angular direction of precession of the magnetic moments and the other component will be rotating in the opposite direction. When the high frequency magnetic intensity is rotating in the same sense as the preferred direction for precession of the magnetic moment, it will couple strongly with the magnetic moment and drive it into precession. When the high frequency magnetic intensity is rotating in the opposite angular direction, however, very little coupling or interaction between the high frequency magnetic intensity and the magnetic moment takes place.

Furthermore, while this difference in coupling and consequent different in permeability for oppositely polarized components is not limited to particular values of frequency or magnetic field strength, certain particularly useful effects are observable at resonance. Referring to FIG. 3, for example, plots **28** and **29** of the attenuation (which corresponds closely to the imaginary portion of the permeability) for the respective positive and negative circularly polarized components of a high frequency magnetic field versus biasing magnetic field for a ferrite medium are shown. From this plot it may be observed that when the natural resonance frequency of the magnetic moment as determined by the strength of the applied field coincides with the driving frequency of the high frequency magnetic field components circularly polarized in the preferred sense, a large amount of power can be absorbed from the driving field. However, very little power is absorbed from the oppositely circularly polarized component.

The element **21** of FIG. 2 is made from a paramagnetic material which has low conductivity. Any of a number of ferromagnetic materials which each comprise an iron oxide in combination with one or more bivalent metals, such as nickel, magnesium, zinc, manganese or other similar material have proved to be satisfactory. These materials combine with the iron oxide in a spinel structure and are known as ferromagnetic spinels or as polycrystalline ferrites. In accordance with the usual practice, these materials are first powdered and then molded with a small percentage of plastic material such as Teflon or polystyrene. As a specific example, the element **21** may be a strip of nickel-zinc ferrite of the approximate chemical formula $(Ni_{.3}Zn_{.7})Fe_2O_3$ prepared as noted above. In addition, commercially available samples of ferrite, and finely powdered conducting ferromagnetic dust in an insulating binder may be employed. By way of inclusion but not of limitation, the phrase "paramagnetic material having low conductivity" is to be construed as applying to the foregoing types of materials. In addition, as employed in the present application and claims, the term gyromagnetic medium is intended to apply to all materials having magnetic properties of the type disclosed in the above-mentioned article by Polder, and as discussed above in conjunction with FIG. 2.

FIG. 4 illustrates a wave guide unit which was actually employed to demonstrate the phenomena discussed in the present specification. This wave guide component comprises a section of wave guide **31**, of rectangular cross-section having a broader cross-sectional dimension as shown in FIG. 4 and a narrower cross-sectional dimension substantially one-half the broader dimension, equipped with conventional coupling elements **32** and **33** at its ends, respectively, and a ferrite vane or septum **34**. Vane **34** may be adjusted transversely in the wave guide by a micrometer-controlled mounting, as shown, and is located centrally between the ends of the section of wave guide **31**.

In more detail, the element of ferrite **34** is mounted on the threaded end of rod **36** of low dielectric constant material by means of the two nuts **45** and **46**. The rod and ferrite vane are maintained in their proper angular orientation by the pin **37** which is secured to the rod **36** and which is restrained from rotation by the slot **38** in the housing **39**. The vane **34** is moved by rotating the knob **41** which is threaded to the housing **39** and is coupled for longitudinal motion with the rod **36**. The position of the vane **34** within the guide **31** may be determined from the vernier calibrations **42, 43** on the knob **41** and the housing **39**, respectively. Intermediate the ends of the wave guide section **31** and opposite the end of rod **36**, a removable element **44** is provided to give access to the plastic nut **45** which holds the vane **34** against the other nut **46** and onto the rod **36**. With the element **44** removed, nut **45** and vane **34** may be removed and a different vane may be inserted from one end of the wave guide and mounted on rod **36**, so that measurements with various types and shapes of vanes may be made. The structure **48** shown in dotted lines is a flange which holds the housing **39** and the wave guide **31** together.

FIG. 5 is an enlarged cross-sectional view taken along the line indicated at 5—5 of FIG. 4. The section is taken parallel to the narrower side wall of the wave guide and shows the tapered vane or septum of ferrite **34** and the nut **45**.

In FIG. 6, the results of a set of measurements using the device of FIGS. 4 and 5 are shown graphically. In this set of measurements, the vane or septum **34** was formed of a ferrite having a resistivity of 100 ohm centimeters and had a chemical composition $(Zn_{.5}Mn_{.5})Fe_2O_3$. The frequency of the electromagnetic waves was 23,725 megacycles, and the vane or septum **34** was magnetized to ferromagnetic resonance for the characteristics of curves **52** and **53**. The plot **51** was obtained with no biasing magnetic field, the plot **52** was obtained with a transverse biasing field of 4,470 oersteds in one direction, and the plot **53** was obtained with a biasing field of 4,250 oersteds in the opposite sense. It is believed that a slight anisotropy in the internal magnetic field of the sample caused the difference in biasing magnetic fields required for resonance and the resultant slight difference in attenuation peaks. It should be noted that only the central portion of the wave guide is shown in FIG. 6. Specifically, the wave guide is 420 mils wide and the center line of the wave guide section falls at 135 mils on the scale used in this FIG. 6. While the values of attenuation indicated in the plot of FIG. 6 are rather high, it is to be understood that with other samples, similar characteristics having lower levels of attenuation may be readily obtained. One way in which this can be accomplished is by reducing the concentration of paramagnetic material either by using a thinner vane or by using a higher proportion of dielectric binder to paramagnetic material.

It may be observed from the plots of FIG. 6 that the maximum difference in attenuation for the oppositely directed biasing fields obtains when the paramagnetic elements are located substantially off-center in the wave guide but still fairly close to the center of the guide. Specifically when the term "substantially off-center" is employed in the present specification and claims, this signifies that the center of the paramagnetic septum is at least 1 or 2 percent of the distance from the center of the wave guide toward one wall.

FIG. 7 is a block diagram illustrating a typical application of an isolator in accordance with the invention. In this case, the microwave sources **61** and **62** feed the same output circuit **63** and it is desired that no microwave energy be coupled from source **62** into source **61**. An isolator **64** in accordance with FIG. 2 is accordingly placed between the sources **61** and **62**. This isolator, when a suitable biasing magnetic field is applied thereto, effectively blocks transmission from microwave source **62** to source **61** as indicated by point **66** on line **67** of FIG. 6, while allowing a substantial amount of transmission in the opposite direction, as indicated by point **68** on line **67** of this same FIG. 6. When the double pole double throw switch **26** of FIG. 2 is reversed, however, the directions of easy transmission and effective isolation would, of course, be reversed. From the schematic showing of FIG. 7, it is evident that isolators in accordance with the present invention would be useful to prevent "frequency pulling" of a microwave source by reflections from an impedance discontinuity such as is frequently presented by an antenna.

FIG. 8 illustrates the principles of the invention as applied to a dielectric wave guide of the type disclosed in A. G. Fox application Serial No. 274,313, filed March 1, 1952, now Patent 2,794,959, granted June 4, 1957. As shown in FIG. 8, the wave guiding structure comprises an elongated element of dielectric material **71**, which has one cross-sectional dimension substantially greater than the other in order to maintain proper electromagnetic field orientation. The transversely polarized strip of ferrite **72** which is embedded off-center in the dielectric wave guide **71** serves the same isolation purpose for the dielectric wave guide **71** as the element **21** of FIG. 2 does for the wave guide **11**. This paramagnetic element **72** may be permanently magnetized or be magnetized by a suitable electromagnet spaced from the wave guide **71** and having a core of low conductivity paramagnetic material, so as not to distort that portion of the field pattern which is external to the guide. It may be noted that the transverse magnetization will again produce the desired relationship of biasing magnetic field perpendicular to the circularly polarized components of the high frequency magnetic intensity.

It is to be understood that the above-described arrangements are simply illustrative of the principles of the invention. Numerous other arrangements using other known types of electromagnetic wave guiding structures or employing gyromagnetic materials polarized at field strengths other than at resonance may readily be devised by those skilled in the art, for example, without departing from the spirit and scope of the invention.

What is claimed is:

1. A device for modifying electromagnetic wave energy propagation comprising a section of bounded wave guide having a boundary of rectangular transverse cross-section and continuous conductivity, means for applying electromagnetic wave energy having a solely transverse electric field pattern with a region of maximum electric intensity to said section, a longitudinally extending vane element of gyromagnetic material located within said section in the path of and in coupling relationship with said energy, and means for applying a steady magnetic field to said gyromagnetic element, said element being disposed substantially asymmetrically in the transverse cross-section of said wave guide section and centered in a region of electric intensity substantially less than said maximum by an amount sufficient to substantially enhance the modifying effect of said material upon the propagation of said energy over that for said element centered in said region of maximum electric intensity.

2. In combination, a wave guide structure having mutually perpendicular transverse dimensions which are different, means for applying a traveling electromagnetic wave in a frequency range including a given operating frequency to said wave guide having a component of the magnetic field thereof extending in a first direction, a comparatively thin, flat, elongated element of gyromagnetic material which extends longitudinally for at least a wavelength of said energy at said operating frequency located off center upon the larger transverse dimension of said wave guide and in coupling relationship with respect to said traveling electromagnetic wave, means for applying a transverse biasing magnetic field to said gyromagnetic element in a second direction at right angles to said first direction so that said element influences the propagation of said wave to a first extent, and means for applying a selected one of said component field and said biasing field to said gyromagnetic element in a direction opposite from said first named direction for said selected field so that the influence of said element is substantially different from said first extent.

3. A device for modifying electromagnetic wave energy propagation comprising a section of bounded wave guide having a boundary of rectangular transverse cross-section and continuous conductivity, means for applying to said section electromagnetic wave energy having a solely transverse electric field pattern with a region of maximum electric intensity, a longitudinally extending vane of gyromagnetic material located within said section in the path of and in coupling relationship with said energy, and means for applying a steady magnetic field to said gyromagnetic vane in a direction parallel to the electric field lines of said transverse electric field pattern, said vane being disposed substantially asymmetrically in the transverse cross-section of said wave guide section and spaced from both narrow walls of said section and centered in a region of electric intensity substantially less than said maximum by an amount sufficient to substantially enhance the modifying effect of said material upon the propagation of said energy over that for said vane centered in said region of maximum electric intensity.

4. In combination, a generally rectangular wave guide having a boundary of continuous conductivity with broad and narrow walls, an elongated vane of gyromagnetic material located off center toward one of said narrow walls within said wave guide, means for applying a traveling electromagnetic wave to said wave guide having a component of the magnetic field thereof extending in a first direction, means for applying a transverse biasing magnetic field to said gyromagnetic vane in a second direction at right angles to said first direction whereby said vane influences the propagation of said wave to a first extent, and means for applying a selected one of said component field and said biasing field to said gyromagnetic vane in a direction opposite from said first named direction for said selected field whereby the influence of said vane is substantially different from said first extent.

5. A device for modifying electromagnetic wave energy propagation comprising a section of bounded wave guide having a boundary of rectangular transverse cross-section and continuous conductivity, means for applying electromagnetic wave energy having a solely transverse electric field pattern with a region of maximum electric intensity to said section, a longitudinally extending vane element of gyromagnetic material located within said section in the path of and in coupling relationship with said energy, and means for applying a steady magnetic field to said gyromagnetic element in a direction parallel to the electric field lines of said transverse electric field pattern, said element being disposed substantially asymmetrically in the transverse cross-section of said wave guide section and centered in a region of electric intensity substantially less than said maximum by an amount sufficient to substantially enhance the modifying effect of said material upon the propagation of said energy over that for said element centered in said region of maximum electric intensity.

6. In combination, a wave guiding structure having a boundary of rectangular transverse cross-section and continuous conductivity comprising pairs of opposed broad

and narrow walls for support of waves of dominant mode high frequency electromagnetic wave energy at the operating frequency, and a vane of gyromagnetic material extending longitudinally within said structure in energy coupling relationship with the wave energy guided thereby, said vane being magnetically polarized in a plane normal to the longitudinal extend of said vane and parallel to said narrow walls, said vane being located significantly asymmetrically within the transverse cross-section of said structure and symmetrically centered upon a line located between one narrow wall of said structure and a plane parallel to said narrow walls containing the longitudinal center line of said structure.

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