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BROADBAND RESONANCE GYROMAGNETIC ABSORPTION ISOLATOR
WITH MAGNETIC FIELD OF INCREASED
STRENGTH TOWARD NARROW WALL
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3,142,026

FIG. 1

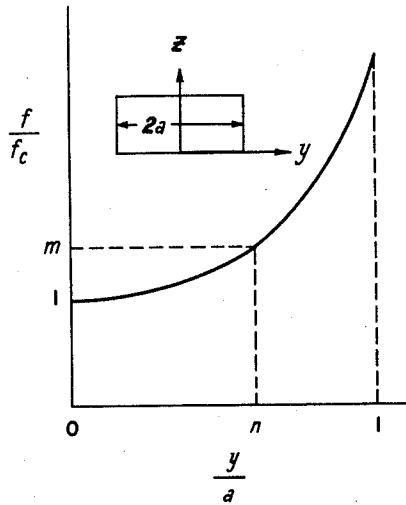


FIG. 2

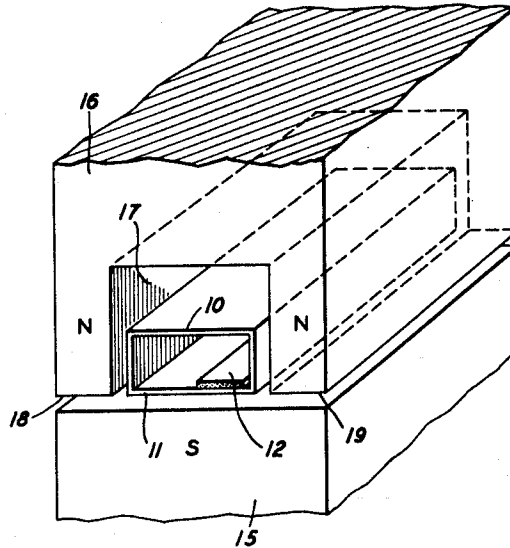


FIG. 3

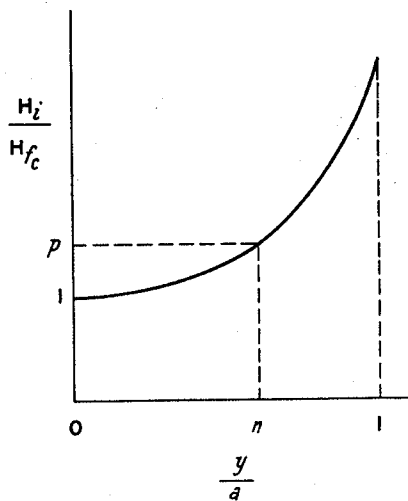
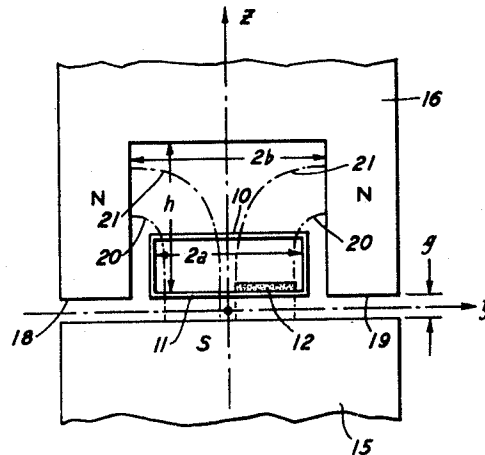


FIG. 4



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4 Claims. (Cl. 333—24.2)

This invention relates to improved nonreciprocal gyromagnetic components for electromagnetic wave transmission systems and, more particularly, to broadband nonreciprocal attenuating devices employing the gyromagnetic properties of certain gyromagnetic materials.

It has been proposed to place an element of gyromagnetic material, such as ferrite, in the path of and asymmetrically in the field pattern of electromagnetic wave energy and to bias this material to the point at which it becomes resonant in a gyromagnetic sense to the frequency of the applied wave energy. When microwaves propagating in one direction are applied to such a path they are greatly attenuated, but when they are propagating in the other direction little attenuation is observed. Such devices are known in the art as isolators. It is often desirable that the effects for each of the respective directions be as large as possible, as greatly different from each other as possible and as independent of frequency as possible.

The devices of the preceding type derive their nonreciprocity from the fact that in a rectangular waveguide there is a plane parallel to the narrow wall thereof in which the radio frequency magnetic field of energy supported in the guide has a transverse field component and a longitudinal field component of equal amplitudes. The two components are out of phase by 90 degrees so that the net field is circularly polarized and appears to rotate in one sense for one direction of propagation along the guide and in the opposite sense for propagation in the opposite direction. Gyromagnetic material located in this plane reacts in respectively different ways with the components rotating in the opposite senses. The physical position of this plane, however, depends upon the frequency of the wave energy and, therefore, a fixed element will include a frequency dependent ratio of components that are purely circularly polarized in the desired sense and a minority of components that appear to rotate in a sense opposite to the preferred and dominating sense. Since these minority components dilute the nonreciprocal effect in the device by increasing the forward loss in an isolator and decreasing its isolation ratio, their presence renders the device highly frequency selective.

Successful but limited attempts have been made to improve this frequency sensitivity by locating an element of nonmagnetic material having a relatively high dielectric constant contiguous to the gyromagnetic element so that the amount of the desired circular polarization within the gyromagnetic element is increased with a corresponding increase in its nonreciprocal effect and decrease in its frequency sensitivity. Examples of this type of improvement are described in the copending application of M. T. Weiss, Serial No. 549,795, filed November 29, 1955, now abandoned, and in an article entitled, "A High Average Power Broad-Band Ferrite Load Isolator for S-Band," by E. W. Skomal, in the IRE Transactions on Microwave Theory and Techniques, January 1959, at page 174.

Even though this loading minimizes the change of position of circular polarization, the bandwidth of the isolator is still limited by the linewidth of the gyromagnetic material. Attempts have been made to broaden the effective linewidth by applying an inhomogeneous biasing magnetic field to the material but unless special precautions are taken this has the effect of increasing the forward loss.

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One such special precaution is disclosed in the copending application of W. W. Anderson and M. E. Hines, Serial No. 6,393, filed February 3, 1960, now Patent No. 3,051,908, and involves a heavy capacitive loading of the transmission line.

It is an object of the present invention to simplify and improve the means for broadening the bandwidth of the nonreciprocal effect of devices employing magnetically polarized elements of gyromagnetic material.

It has been recognized that the region of optimum circular polarization in a rectangular waveguide moves toward the side all of the guide as the frequency of the wave energy is increased. Thus, in accordance with the present invention, the performance of the device is improved by employing an element of gyromagnetic material of narrow resonance linewidth and biasing it with an inhomogeneous biasing field that increases toward the side wall in a way that coincides with the movement of the region of circular polarization with frequency. Thus, each transverse portion of the element is resonant only at that frequency for which that portion sees the circularly polarized radio frequency field. If the material has a narrow resonance linewidth other portions of the element do not contribute much to the forward loss.

A feature of the present invention resides in the simple and novel pole piece geometry by which the required variation of the biasing magnetic field is produced. In one embodiment to be described, the waveguide section containing the gyromagnetic material is received through a channel cut entirely in one pole piece. By properly proportioning the height and width of the channel, the magnetic field intensity distribution across the guide and, therefore, the resonance frequency distribution across the material are made very similar to the distribution of the region of circular polarization with frequency across the guide.

These and other objects and features, the nature of the present invention and its various advantages, will appear more fully upon consideration of the specific illustrative embodiments shown in the accompanying drawings and described in detail in the following explanation of these drawings.

In the drawings:

FIG. 1, given by way of explanation, represents the frequency variation of pure circular polarization across one half of the wide dimension of a rectangular waveguide;

FIG. 2 is a perspective view of a preferred embodiment of the invention showing the relative shapes and locations of the magnetic pole piece, the waveguide and the gyromagnetic element;

FIG. 3, given by way of explanation, represents the magnetic field intensity distribution across one half of the wide dimension of a rectangular waveguide; and

FIG. 4 is a detail cross-section of the structure shown in FIG. 1.

It is known that the position of the region of pure circular polarization in a rectangular dominant mode waveguide can be expressed:

$$\tan \frac{\pi y}{2a} = \sqrt{\left(\frac{f}{f_c}\right)^2 - 1} \quad (1)$$

where y is the distance from the center of the guide to the position of circular polarization, $2a$ is the width of the rectangular guide, f_c is the cut-off frequency of the dominant TE_{10} mode, and f is the frequency of the applied wave energy. In the usual frequency range of the TE_{10} mode,

$$\frac{\pi y}{2a} < 1 \quad (2)$$

and Equation 1 can be approximated as

$$\frac{f}{f_c} \approx 1 + \frac{1}{2} \left(\frac{\pi y}{2a} \right)^2 \quad (3)$$

A plot of Equation 3 on FIG. 1 clearly shows that for the lower frequencies near to the cut-off frequency the region of pure circular polarization is very near the center of the guide as represented by the abscissa value $y/a=0$. As the frequency is increased, this region moves increasingly closer to the side wall as represented by the abscissa value $y/a=1$. It is apparent, therefore, why there has been considerable difficulty in broadbanding gyromagnetic devices which depend for their operation upon the location of this region.

Referring more specifically to FIG. 2, a nonreciprocal device overcoming this difficulty is shown as an illustrative embodiment of the invention. The structure comprises a section 10 of conductive rectangular waveguide which is to be interposed in the path of linearly polarized wave energy requiring isolation, such as between a source and a load. Guide 10 has conductive wide walls of internal transverse dimension $2a$ of at least one-half wave length of energy to be conducted thereby and a narrow dimension substantially less than one-half of the wide dimension in accordance with usual design considerations.

Disposed on one side of the center line of guide 10 is an elongated gyromagnetic element 12 running adjacent to the bottom wall 11 of guide 10. Element 12 has a thin transverse cross-section of rectangular shape with a large width dimension that is a substantial fraction of the waveguide width extending parallel to wall 11. Element 12 extends longitudinally along guide 10 for an interval of several wave lengths. The remainder of guide 10 is filled by a dielectric medium, such as air, of low dielectric constant substantially less than dielectric constant of element 12.

The material of element 12 is of the type having electrical and magnetic properties of the type described by the mathematical analysis of D. Polder in *Philosophical Magazine*, January 1949, volume 40, pages 99 through 115. More specifically, element 12 may be made of any nonconducting ferromagnetic material. For example, it may comprise iron oxide with some of the oxides of one or more bivalent metals such as nickel, magnesium, zinc, manganese, or aluminum, combined in a spinel crystal structure. This material is known as a ferromagnetic spinel or as ferrite. Since a narrow resonance linewidth is preferred for the invention as will be discussed hereinafter, element 12 may comprise one of the ferromagnetic garnet materials. Any of these materials are sometimes first powdered and then molded with a small percentage of a plastic binder. Hereinafter the term "ferrite" will be used exclusively as descriptive of the material, but it will be understood that equivalent materials having similar gyromagnetic properties may be used to practice the invention.

In accordance with a broad aspect of the present invention, element 12 is biased or polarized by an external magnetic field applied at right angles to the direction of propagation of wave energy along guide 10 that varies transversely across the guide in such a way that each portion of element 12 is resonant at the frequency which is circularly polarized in that portion. Referring back to FIG. 1, it will be seen that at some arbitrary fraction n of the distance across the guide, wave energy is purely circularly polarized only for that frequency bearing the specific ratio of m to the cut-off frequency. Therefore, the strength of the external biasing field for element 12 is so tapered that independent grains of element 12 lying along the thin, longitudinally extending strip at the position n are resonant in a gyromagnetic sense at the frequency m and so that those grains in portions to the right and left of n are resonant respectively at frequencies above and below m . The biasing field must, therefore, have the proper strength in the center of the guide to pro-

duce resonance at approximately the cut-off frequency f_c and increase toward the side wall according to a function similar to Equation 3. Such a characteristic is shown in FIG. 3. When properly evaluated as set forth hereinafter, any point n across the guide will have the proper field p to produce resonance at the frequency m .

In accordance with the invention, this field distribution is produced by the novel pole piece geometry shown in perspective in FIG. 2 and in the more detailed cross-sectional view thereof in FIG. 4. Referring again to FIG. 2 or to FIG. 4, the structure comprises one pole piece 16 formed from a block of magnetic material having a longitudinally extending rectangular channel 17 cut along the full length of its face. Channel 17 has width $2b$ parallel to the wide dimension of guide 10, a depth h parallel to the narrow dimension of guide 10 and extends longitudinally for at least the length of element 12. The over-all width of pole 16 is wider than guide 10 so that the remaining portions 18 and 19 on either side of channel 17 may extend on either side of guide 10 to terminate in the plane of wall 11. Pole 16 is opposed by a second pole piece 15 of plane pole surface separated from the faces of 18 and 19 by the very small air gap g . Poles 15 and 16 are oppositely magnetized as represented by the designation N on portions 18 and 19 of pole 16 and the designation S on pole 15 by suitably wound turns of wire connected to proper sources of potential or the pole pieces may be parts of a permanently magnetized structure.

Since element 12 is thin and disposed on the wall adjacent to plane pole 15, the field within element 12 is substantially normal to the magnetic plane of guide 10. The depth h of channel 17 is sufficiently large that its root surface has little effect on the field distribution within the channel. Thus, the magnetic structure in effect comprises a pair of pole pieces 18 and 19 of one polarity disposed adjacent to and slightly spaced from the narrow wall of guide 10 and a third pole piece 15 of the opposite polarity disposed along the wider wall of the guide. The intensity distribution of the field produced by such a structure is nonuniform transversely across element 12 because the portions thereof near the center of guide 10 has a much smaller field intensity due to the longer path 21 between the N and S poles than the shorter path 20 for portions thereof near the narrow walls of guide 10. More particularly, it may be shown that the external field H_e along the lower surface of element 12 when h is sufficiently large is

$$\frac{H_e}{H_{e0}} = \sec \left(\frac{\pi y}{2b} \right) \approx 1 + \frac{1}{2} \left(\frac{\pi y}{2b} \right)^2 \quad (4)$$

where H_{e0} is the field at the center of the surface where $y=0$ and $z=0$.

The internal field H_i within element 12 determines its resonant frequency and is

$$H_i = H_e - 4\pi M \quad (5)$$

where $4\pi M$ is the saturation magnetization of the material of element 12. Therefore,

$$\frac{H_i}{H_{e0}} \approx 1 + \frac{1}{2} \left(\frac{\pi y}{2b} \right)^2 - \frac{4\pi M}{H_{e0}} \quad (6)$$

In accordance with the present invention it has been recognized that if two conditions are met:

(1) That the magnetic field strength H_{e0} is that necessary to produce the internal field H_{ic} which in turn produces resonance at f_c that is,

$$H_{e0} = H_{ic} + 4\pi M \quad (7)$$

and

(2) That the ratio of the width of guide 10 to the width of channel 17 is such that

$$\frac{a^2}{b^2} = 1 - \frac{4\pi M}{H_{e0}} = \frac{H_{ic}}{H_{ic} + 4\pi M} \quad (8)$$

then Equation 6 may be reduced to

$$\frac{H_i}{H_{ic}} \approx 1 + \frac{1}{2} \left(\frac{\pi y}{2a} \right)^2 \quad (9)$$

When these two conditions are met, or at least substantially approximated, it may be seen by comparison with Equation 3 above that the magnitude of the biasing magnetic field changes along the y direction in the same way as does the position of pure circular polarization. Thus, the location represented by n on FIGS. 1 and 3 will have a biasing field strength represented by p that will produce resonance at the frequency represented by m , the frequency having pure circular polarization at n .

It was noted above that the material of element 12 is preferably one of narrow resonance linewidth. The significance of this requirement will be understood when it is recalled that positive and negative circular polarizations are mixed at positions a little removed from the position of pure circular polarization. Thus, if the linewidth of the material is not infinitely small, the material will absorb part of the incident wave in proportion to the linewidth. This increases the desirably low ratio of incident or forward loss to reflected or backward loss of the isolator. Calculations at X-band have, however, shown that for materials of linewidth of less than 730 oersteds, the ratio of the forward loss to the backward loss is smaller than 0.01. Better ratios will be obtained for material of smaller linewidth and materials of linewidths less than 730 oersteds are abundant.

While the magnetic pole structure illustrated appears to be novel and to have particular advantages in its simplicity of construction and in the ease with which design calculations for it may be made, it should be understood that the broader principles of the invention relating to the desired intensity distribution of the magnetic biasing field may be practiced with substantially different pole structures. For example, the precise shape of channel 17 and the outside contour of pole pieces 15 and 16 appear to be matters that allow considerable variation.

In all cases it is to be understood that the above-described arrangements are merely illustrative of a small number of the many possible applications of the principles of the invention. Numerous and varied other arrangements in accordance with these principles may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A nonreciprocal device for electromagnetic wave energy comprising a section of waveguide having opposed pairs of wide and narrow walls, a longitudinally extending element of gyromagnetic material of narrow resonance linewidth located within said guide and extending for a substantial transverse extent on one side of the longitudinal center line of said guide, means for applying a magnetic field to said element that increases in strength toward the narrow walls of said guide according to a parabolic function, said means comprising a member of magnetic material having a pair of pole pieces both of a first polarity that extend on either side of said guide adjacent to said narrow walls and a member of magnetic material of a polarity opposite to said first polarity extending adjacent to a wide wall of said guide and opposing said pole pieces.

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tudinal center line of said guide, means for applying a magnetic field to said element that increases in strength toward the narrow walls of said guide according to a parabolic function, said means comprising a member of magnetic material having a pair of pole pieces both of a first polarity that extend on either side of said guide adjacent to said narrow walls and a member of magnetic material of a polarity opposite to said first polarity extending adjacent to a wide wall of said guide and opposing said pole pieces.

2. The device according to claim 1 wherein the distance between said opposed narrow walls is $2a$ and wherein the distance between said pole pieces adjacent to said narrow walls is $2b$ and wherein said distances have a ratio between them according to

$$\frac{a^2}{b^2} = 1 - \frac{4\pi M}{H_{e0}}$$

wherein H_{e0} is the strength of said applied magnetic field at the center of said guide and wherein $4\pi M$ is the saturation magnetization of said gyromagnetic material.

3. The device according to claim 2 wherein said field strength H_{e0} is that necessary to produce gyromagnetic resonance in said material at the cut-off frequency of said waveguide.

4. A nonreciprocal device for electromagnetic wave energy comprising a section of waveguide having a boundary of rectangular transverse cross-section, a longitudinally extending element of gyromagnetic material of narrow resonance linewidth located within said guide and extending for a substantial transverse extent on one side of the longitudinal center line of said guide, means for applying a magnetic field to said element that increases in strength toward the narrow walls of said guide according to a parabolic function, said means comprising a first pole piece formed from a block of magnetic material having a channel cut along its face with said guide received in said channel, and a second pole piece opposing said first pole piece and substantially closing one side of said channel.

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