

June 26, 1962

R. KOMPFFNER ETAL

3,041,559

MICROWAVE FILTER

Filed Aug. 27, 1959

2 Sheets-Sheet 1

FIG. 1

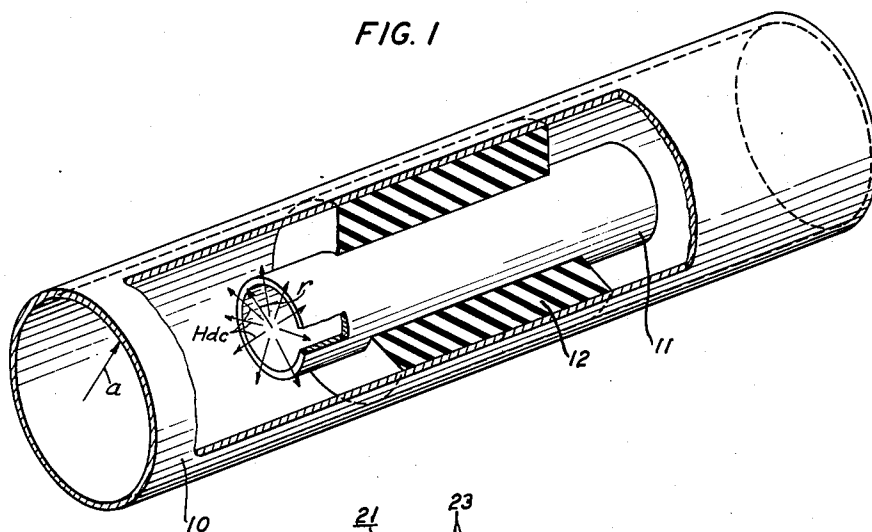


FIG. 2

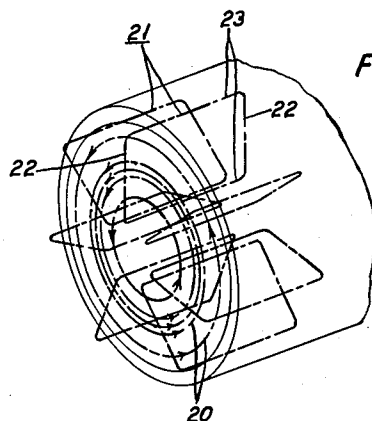
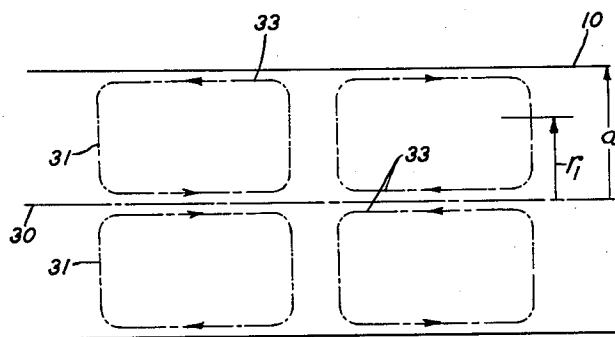


FIG. 3



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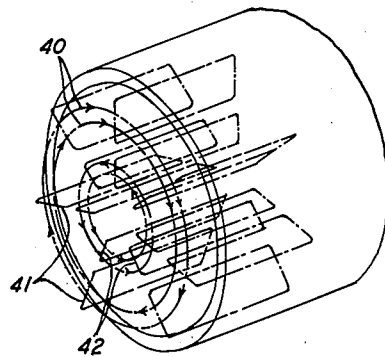


FIG. 4

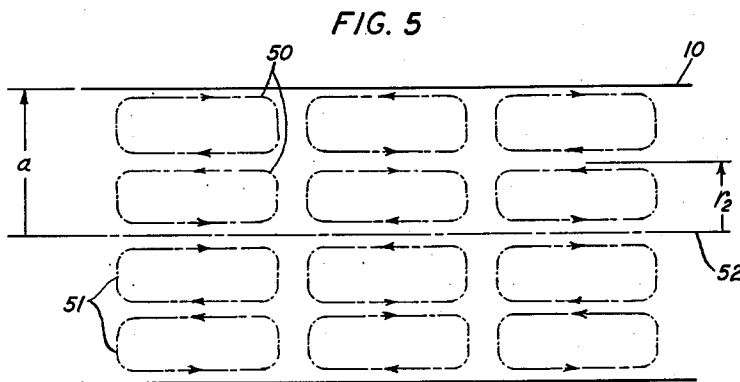


FIG. 5

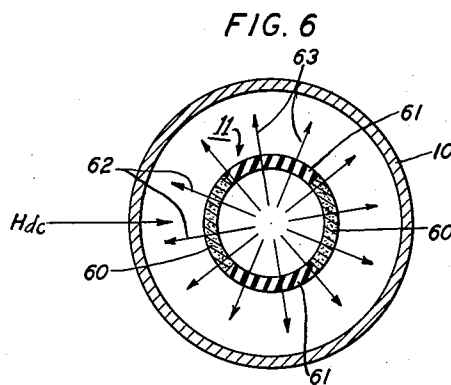


FIG. 6

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3,041,559

MICROWAVE FILTER

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This invention relates to electromagnetic wave transmission systems and in particular to mode filters for selectively attenuating higher order circular electric mode wave energy.

In the transmission of electromagnetic wave energy through a hollow conductive pipe, or other waveguide, it is well known that the energy can propagate in one or more transmission modes, or characteristic field configurations, depending upon the cross-sectional size and shape of the particular guide and the operating frequency. It is also well known that the larger the cross section of the guide is made, the greater is the number of modes in which the energy can propagate at any given operating frequency. Generally, it is desirable to confine the propagation of the energy to one particular mode, chosen because its propagation characteristics are favorable for the particular application involved. However, these considerations may dictate the use of guide sizes which accommodate both the desired mode and other higher order modes of the same family or modes having other basic configurations. This is particularly true of systems employing the TE_{01} circular electric mode. As is well known, the propagation of microwave energy in the form of the TE_{01} mode in circular waveguides is ideally suited to the long-distance transmission of high-frequency wide-band signals since the attenuation characteristic of this transmission mode, unlike that of other modes, decreases with increasing frequency. Furthermore, the transmission loss for the circular electric mode is inversely related to the guide diameter. Hence, the practice, whenever possible, is to make long uninterrupted runs of waveguide with relatively large diameter pipe. However, the use of such large pipe makes such a system susceptible to the generation of incidental spurious modes which, because of the large guide size, can propagate right along with the desired mode.

In an ideal system which has a waveguide that is perfectly straight, uniform, and conducting, the propagation of TE_{01} waves therethrough would be undisturbed, and the fact that the guide is capable of supporting other modes would not be a problem. However, multiplexing operations and bends in the system necessitate diameter changes which tend to disturb the TE_{01} circular electric mode with the resulting conversion of power from the desired mode into other spurious and undesired modes. The latter modes being fully capable of being propagated within the guide along with the desired mode, have a deleterious effect upon the system. Obviously, every effort must be made to minimize the generation of spurious modes by appropriate means. However, there is a point beyond which such measures become uneconomical. It then becomes necessary to accept whatever spurious mode energy is produced and to provide filtering means intermittently spaced along the wave path for its elimination.

It should be noted that there are two general classifications into which the spurious modes fall. The first is the noncircular modes which can, in general, be easily filtered from the system. The second class of spurious modes are the higher order circular electric modes which are not as readily removable in that their field configuration tends to be similar to that of the TE_{01} mode. In

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the past, filtering techniques effective for the noncircular modes have been ineffective in removing the higher order circular modes, and filtering arrangements which operated effectively on the spurious circular modes had likewise seriously attenuated the desired mode.

It is therefore an object of this invention to selectively attenuate higher order circular electric mode wave energy and to transmit substantially unaffected the TE_{01} circular electric mode wave energy.

In accordance with the present invention, the phenomenon of gyromagnetic resonance is utilized to provide the loss mechanism for the attenuation of the spurious wave energy. In specific embodiments of the invention, resonantly biased gyromagnetic material is located within a circular waveguide so as to interact with the longitudinally extending radio frequency magnetic fields associated with the modes to be suppressed. In particular, if the cylinder of gyromagnetic material has a radius r equal to 0.628 times the radius of the guide, the TE_{01} mode, which has a zero amplitude longitudinal magnetic field component at that radius, is transmitted substantially unaffected, whereas the resonantly biased gyromagnetic material strongly interacts with the TE_{02} mode, and to a varying degree, with the other higher order circular electric modes.

To avoid interaction between the radial magnetic field components of the preferred mode and the gyromagnetic material, special precautions must be observed relating to the orientation of the biasing field or the location of the gyromagnetic material. These precautions are indicated by means of the several illustrative embodiments of the invention as hereinafter described.

In a first preferred embodiment of the invention, a thin cylinder of radially biased gyromagnetic material is coaxially disposed within a cylindrical waveguide. The radius of the cylinder is selected to locate the gyromagnetic material within a region of the guide wherein the longitudinal magnetic field components for the preferred mode is a minimum. So biased and located, the gyromagnetic material is everywhere polarized in a direction perpendicular to the longitudinal magnetic field components of the spurious modes (which are substantial in the region of the material) and simultaneously polarized in a direction parallel to the radial magnetic field components of the preferred mode. With this particular location of the cylinder and spatial orientation of the biasing and the radio frequency fields, there is strong coupling between the field components of the spurious modes and the resonantly biased gyromagnetic material but minimum interaction between the latter and the preferred mode.

In a second embodiment of the invention, a simplified biasing field configuration is used. In this embodiment the gyromagnetic material is uniformly biased by a substantially parallel external field in a direction transverse to the direction of wave propagation. However, to avoid coupling between the gyromagnetic material and the radial field components of the preferred mode, the coaxial cylinder is longitudinally segmented into four portions. One pair of oppositely disposed segments is made of gyromagnetic material whereas the other pair of segments consists of nongyromagnetic material. The gyromagnetic segments are placed in those regions of the guide wherein the radial field components for the preferred mode are substantially parallel to the biasing field. So oriented there is substantially no transfer of power from the preferred mode to the resonantly biased gyromagnetic material. The radial field components that are substantially normal to the biasing field, on the other hand, pass through the nongyromagnetic segments and consequently there is no resulting interaction therewith and no result-

ing attenuation. Attenuation of the spurious modes, as before, results from the interaction of the longitudinal magnetic field components of these modes with the gyromagnetic material which, throughout the gyromagnetic material are normal to the biasing field and consequently favorably oriented to couple to the gyromagnetic material.

Because of the impracticability of radially biasing the gyromagnetic cylinder as required in the first embodiment by external means, self-biasing techniques are described in detail below.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view of the first embodiment of the invention showing a coaxial cylinder of gyromagnetic material radially biased;

FIGS. 2 and 3 illustrate the electric and magnetic field patterns of the TE_{01} mode;

FIGS. 4 and 5 illustrate the electric and magnetic field patterns of the TE_{02} mode, and

FIG. 6 shows a second embodiment of the invention using a segmented cylinder externally biased.

Referring more particularly to FIG. 1, there is shown a section 10 of hollow conductive waveguide having a circular transverse cross section of radius a , sufficiently large to support the TE_{01} mode, and numerous higher order circular electric modes. Coaxially disposed within guide 10 is a hollow cylinder of gyromagnetic material 11. The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetically polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a significant precessional motion at a frequency within the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion, which is characterized as having an angular momentum and a magnetic moment, has a natural frequency proportional to the intensity of the polarizing field. At the particular value of polarizing field at which the natural precessional frequency of the magnetic moments is equal to that of the orthogonally directed high-frequency magnetic field components, the condition of gyromagnetic resonance is produced, and large amounts of power can be extracted from the high-frequency wave energy and absorbed in the gyromagnetic material. High-frequency magnetic field components parallel to the biasing field, however, do not interact with the atomic spin systems of the gyromagnetic material and consequently are incapable of coupling power thereto. Typical of those materials displaying such properties are ionized gases, paramagnetic materials and ferromagnetic materials, the latter including the spinels such as magnetism, aluminum ferrite and aluminum zinc ferrite, and the garnet-like materials such as yttrium-iron garnet.

In the embodiment of FIG. 1, cylinder 11 is biased by a radially directed steady magnetic field H_{dc} . This biasing field may be supplied by means of externally applied magnetic fields derived from electric solenoids with magnetic cores, from electric solenoids without magnetic cores, and from permanent magnets, or cylinder 11 may be permanently magnetized in a manner to be described hereinafter.

Supporting cylinder 11 in its coaxial position within guide 10 is the hollow dielectric cylinder 12 circumscribing cylinder 11 and otherwise completely filling the guide region between cylinder 11 and guide 10 in a manner well known in the art. Cylinder 12 is preferably made of a low-loss dielectric material having a very low dielectric constant, such as polyfoam, so as to minimize the pos-

sibility of reflections of wave energy incident thereon or other deleterious effects.

FIG. 2 shows the field pattern of the TE_{01} mode. The electric field vectors 20 are represented as concentric circles whose intensities vary sinusoidally from the guide center to the guide wall. Associated with these electric field vectors are the magnetic field vectors 21. These are everywhere normal to the electric vectors 20 and consist of a series of loops having radial components 22 and longitudinal components 23.

In FIG. 3 there is shown a longitudinal section of guide 10 taken through the axis 30. Four representative magnetic field loops are also shown, with typical radial components 31 and longitudinal components 33 indicated. However, as is well known, the magnetic field intensity is not confined solely to the immediate vicinity of any one loop, but varies gradually within the guide, reaching a value of zero in the longitudinal direction at a radius r_1 equal to $0.628a$, where a is the guide radius.

In FIGS. 4 and 5 the TE_{02} mode is similarly represented. However, it may be seen that in passing from the center of the guide to the circumference along the radius there is a reversal in the polarity of the electric field components (and thus an electric field null exists).

Associated with each of the oppositely directed electric fields, are magnetic field loops 41 and 42, whose longitudinal components are a maximum where the electric field components are a minimum. This occurs at the guide center, at the guide wall, and at radius r_2 equal to $0.535a$. This magnetic field distribution is shown in FIG. 5, which is a longitudinal section taken through the axis 52. The figure shows the double loops 50 and 51 on each side of the axis, with adjacent longitudinal field components reinforcing each other to form a maximum field region at radius r_2 .

The operation of the selective mode filter of FIG. 1 may now be properly comprehended with the aid of the field patterns of FIGS. 3 and 5. Electromagnetic wave energy consisting primarily of TE_{01} mode energy and spurious higher order circular electric modes is introduced at one end of guide 10. This energy propagates through the guide until it reaches the resonantly biased gyromagnetic cylinder 11, which is proportioned to have a mean radius r equal to $0.628a$. As explained above, the TE_{01} mode wave energy has longitudinal magnetic field components which are a minimum at this radius so that there is negligible interaction between the TE_{01} wave and the transversely, resonantly biased gyromagnetic material. However, the higher order modes, and particularly the TE_{02} mode, have substantial longitudinal magnetic field components which strongly interact with the precessing atomic components in the gyromagnetic material and there is, consequently, a substantial transfer of energy between the propagating waves and the cylinder 11. This transfer of energy is accompanied by a substantial attenuation of the higher order modes with little attenuation of the TE_{01} mode.

In the embodiment of FIG. 1, the steady biasing field H_{dc} is radially applied to cylinder 11 so as to be at all times perpendicular to the longitudinal magnetic field components of the propagating waves. In this manner, the radio frequency field components and the biasing fields have at all points the necessary spatial orientation to cause a transfer of power between the incident wave energy and the resonantly biased gyromagnetic material. From the description of the field configurations of the circular electric mode wave energy as given above and illustrated in FIGS. 2-5, it is seen that there is, in addition to the longitudinal component of the radio frequency field, a radial component also capable of interacting with the gyromagnetic material and whose presence must be taken into account. In the embodiment of FIG. 1, it will be noted that this field is at all points parallel to the radial biasing field for all the circular electric modes and hence is incapable of interacting with the gyromagnetic material.

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The importance of the particular field orientation is best illustrated by considering a second embodiment of the invention as illustrated in FIG. 6.

In the embodiment of the invention shown in FIG. 6, cylinder 11 is longitudinally segmented for reasons which will become apparent. Two segments 60 are made of a gyromagnetic material. The other two segments 61 are made of a nongyromagnetic material. The minimize any tendency to distort the incident wave energy it is preferable that a nongyromagnetic material having a dielectric constant substantially equal to that of the gyromagnetic material be used. The biasing field H_{dc} is a uniform parallel field applied transversely to the segmented cylinder and of such magnitude as to produce gyromagnetic resonance in the gyromagnetic segments 60. As in the embodiment of FIG. 1, the biasing field is noted to be everywhere normal to the longitudinal magnetic field components of the circular electric mode wave energy. However, it is also noted that this field is also normal to some of the radial magnetic field components of the circular electric modes. In the absence of any special precautions, the radial components that are normal to the biasing field in the region of the gyromagnetic material would interact and transfer power to the gyromagnetic material in a manner identical to that of the longitudinal field components and introduce loss to the preferred TE_{01} mode. In the embodiment of FIG. 6 this tendency is substantially reduced by making the segments 61 of nongyromagnetic materials, and by applying the biasing field substantially parallel to the direction of the radial field lines passing through the gyromagnetic segments 60. So oriented, the radial field components 62 shown in FIG. 6 are substantially parallel to the direction of the axis of the precessing atomic particles in the gyromagnetic material and consequently do not interact therewith. The radial field components 63, however, which are directed substantially normal to the biasing field H_{dc} and which are in a favorable position to induce coupling between the cylinder and the magnetic fields, are in that portion of the cylinder composed of the nongyromagnetic material 61, and consequently there can be no interaction and hence no losses induced in these segments.

Whereas the embodiment of FIG. 6 permits the use of a simpler biasing field configuration, there is an overall reduction in the losses experienced by the spurious modes since the longitudinal field components in the nongyromagnetic segments 61 do not interact with the dielectric material. Consequently, the relative circumferential extent of segments 60 and 61 are a compromise. The larger the gyromagnetic segments the larger the attenuation of both the desired and the undesired modes. With small gyromagnetic segments the TE_{01} losses are small but so is the attenuation of the spurious modes. Therefore, in any given system the distribution of gyromagnetic and nongyromagnetic material within the cylinder must be determined in accordance with the needs of the particular application at hand.

Because of the impracticability of producing the required radial biasing field shown in FIG. 1 by external means, permanent self-biasing means have been utilized. As is well known, gyromagnetic materials have a so-called "built-in" magnetic anisotropy field which can produce resonance just as an externally-applied field would. This anisotropy field arises from the interaction of internal forces in the crystalline structure of the gyromagnetic material. The magnitude of this internal field may vary from about 150 oersteds for yttrium-iron garnet material to as much as 17,000 oersteds or more for Ferroxidure (see "Ferromagnetic Resonance in Ferroxidure" by M. T. Weiss and P. W. Anderson, vol. 98, No. 4, pages 925, 926 of the May 15, 1955 Physical Review). As such, the built-in field can cause resonances to exist at frequencies of from about 500 megacycles to over 50,000 megacycles, depending upon the material used. In the past, the anisotropy field has been regarded as a hindrance,

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placing a lower limit on the resonant frequency at which the gyromagnetic material could be operated. In accordance with the present invention, however, the presence of this natural internal field is utilized to self-bias the gyromagnetic cylinder 11 of FIG. 1. In particular, an "oriented" medium is made by mixing the appropriate gyromagnetic material in the form of a powder in a dielectric binder, such as polyethylene, and allowing the mixture to solidify in a strong external magnetic field. The resulting sheet of gyromagnetic material is then bent into a cylindrical shape, thus obtaining a permanently radially magnetized element of the type required in the embodiment of the invention shown in FIG. 1. In addition to acting as a binder, the dielectric material tends to reduce the overall dielectric constant of the cylinder, making for a much better match.

The choice of gyromagnetic material is, of course, dictated by the operating frequency of the system since an internal field capable of producing gyromagnetic resonance at the operating frequency is desired. By varying the ratio and nature of the dielectric material and the gyromagnetic material, the intensity of the internal field and the dielectric constant of the cylinder may be controlled.

For some materials, such as Ferroxidure which has a hexagonal crystalline structure, an oriented medium may be obtained merely by compressing the gyromagnetic powder in a magnetic field.

A self-biased cylinder may also be constructed by forming small permanent bar magnets in a wedge-shape and placing them adjacent to each other to form a cylindrical surface.

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

What is claimed is:

1. In an electromagnetic wave system, a section of circular waveguide supportive of a plurality of circular electric modes at a given operating frequency, said modes as supported in said guide having longitudinally and radially extending magnetic field components, means for selectively attenuating some of said modes to a substantially greater degree than a given preferred mode of said wave energy comprising a thin element of material capable of exhibiting gyromagnetic properties at said frequency disposed in a region within said guide wherein the longitudinally directed field components for said preferred mode are a minimum, and means for resonantly biasing said material at said frequency in a direction transverse to said longitudinally extending field components and substantially parallel to said radially extending field components.

2. The combination according to claim 1 wherein said element is a hollow cylinder coaxially disposed within said guide.

3. A mode filter comprising a section of hollow circular waveguide supportive of a plurality of circular electric modes at a given operating frequency, a longitudinally segmented thin hollow cylinder coaxially disposed within said guide having a first pair of segments of material capable of exhibiting gyromagnetic properties at said given frequency oppositely disposed along the circumference of said cylinder and interposed between a second pair of non-gyromagnetic segments of dielectric material, and means for magnetically polarizing said first pair of segments to gyromagnetic resonance at said frequency.

4. The combination according to claim 3 wherein said polarizing field is applied normal to the axis of said guide and parallel to the direction of the diameter connecting the midpoints of said first pair of segments.

5. In an electromagnetic wave system supportive of a plurality of circular electric mode waves at a given frequency, means for selectively attenuating the higher order of said modes comprising a section of circular waveguide, a thin cylinder of material capable of exhibiting gyromagnetic properties at the operating frequency of said system coaxially disposed within said section, and means for radially biasing said material to gyromagnetic resonance at said frequency.

6. The combination according to claim 5 wherein said cylinder has a mean radius r equal to $0.628a$, where a is the inside radius of said circular waveguide.

7. A circular electric mode filter comprising a wave path for propagating electromagnetic wave energy in the circular electric mode configuration having longitudinally and radially directed magnetic field components including at least the TE_{01} and TE_{02} modes, means for substantially attenuating said TE_{02} mode comprising a resonantly biased element of material exhibiting gyromagnetic effects disposed in a region of said path wherein the longitudinally directed magnetic field components of said TE_{01} mode are a minimum and wherein the longitudinally directed magnetic field components of said TE_{02} mode are substantial, and means for biasing said element in a direction normal to said longitudinal field components.

8. A method for producing a radially biased cylinder of gyromagnetic material comprising the steps of mixing a gyromagnetic material in the form of a powder in a dielectric binder, forming said mixture into a thin sheet having broad and narrow surfaces, allowing the mixture to

solidify in the presence of an external magnetic field directed perpendicular to said broad surfaces, and bending the resulting sheet into a cylindrical shape where said broad surfaces comprise the inner and the outer surfaces of said cylinder.

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