May 15, 1962 J. J. KOSTELNICK 3,035,235

FIELD DISPLACEMENT ISOLATOR

Filed May 6, 1959

FIG. 1

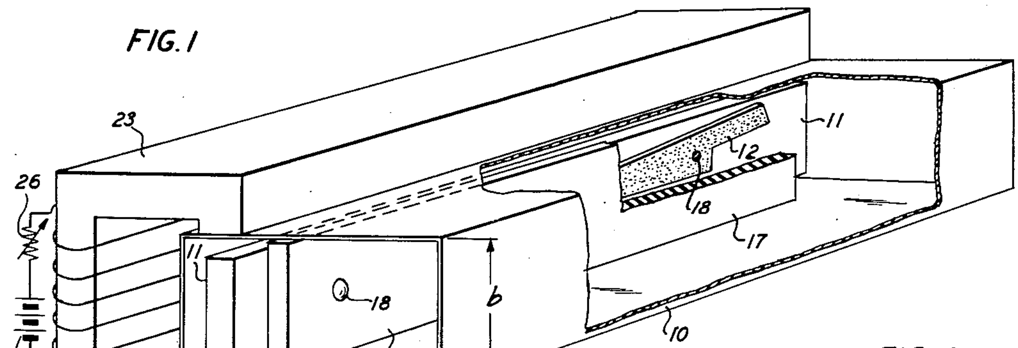


FIG. 2

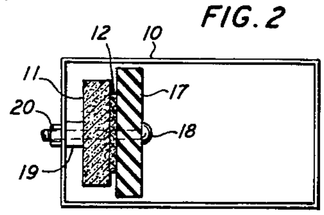


FIG. 3B

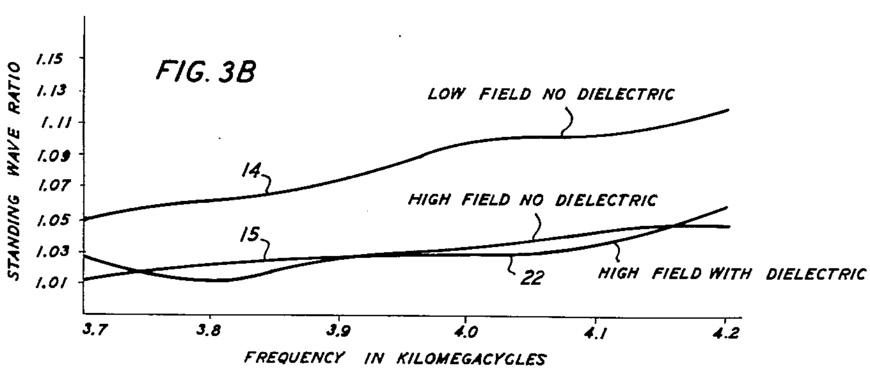
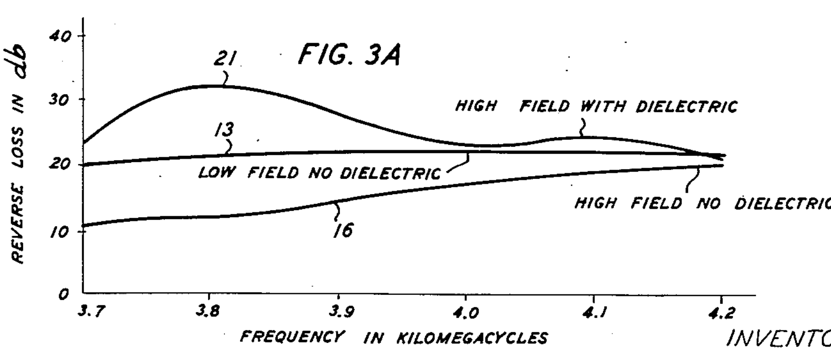


FIG. 3A



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FIELD DISPLACEMENT ISOLATOR

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This invention relates to electromagnetic wave transmission systems and more particularly to transmission structures having nonreciprocal attenuating properties for use in such systems.

The use of materials having gyromagnetic properties to obtain both reciprocal and nonreciprocal effects in microwave transmission circuits is widely known and has found numerous and varied applications in propagation structures of both the wave guide and the transmission line types. A résumé of early work done in this field is contained in an article entitled "The Behavior and Application of Ferrites in the Microwave Region," by A. G. Fox, S. E. Miller, and M. T. Weiss, Bell System Technical Journal, January 1955, pages 5–103. The Proceedings of the IRE, vol. 44, No. 10, October 1956, is devoted in major part to a more recent survey of the uses and characteristics of gyromagnetic material.

Included among the new transmission components that have found widespread use in the microwave art is the so-called "isolator." The isolator may be defined as a circuit element in which electromagnetic wave energy propagating in one direction, designated the forward direction, is but slightly attenuated while wave energy propagating in the other direction, designated the reverse direction, is attenuated to the extent required by the system.

Among the various types of isolators described in the above-mentioned B.S.T.J. article is the so-called "field displacement" isolator. In accordance with one simple explanation of the theory of the prior art field displacement isolator, a null in the electric field configuration of a propagating wave is caused to exist at one longitudinal surface of a gyromagnetic element for the forward propagation direction while a finite, and preferably large, electric field intensity is caused to exist at that same surface for a wave propagating in the reverse direction. Resistive material for producing loss in the reverse direction is disposed on the surface in the electric field null region with the result that very low attenuation occurs for waves propagated in the forward direction but, due to the presence of the large electric field intensity in the region of the resistive material for the reverse direction, significant attenuation of waves propagation in this direction occurs. This attenuation is referred to as the reverse loss of the isolator.

The field displacement isolator has been found attractive for many applications. However, it has recently become evident that the transmission characteristics of the simple resistance sheet-gyromagnetic element structure, when scaled to frequency ranges somewhat lower than those for which the isolator was originally designed, are seriously degraded and in some cases fail to meet minimum system specifications.

It is therefore an object of the present invention to broaden the frequency band over which field displacement isolator principles may be advantageously employed.

Specifically, it has been found that at microwave frequencies of the order of four kilomegacycles per second, the typical field displacement isolator under the influence

of the scaled value of external magnetic biasing field produces a reflected wave having a magnitude considerably greater than is acceptable in most wave guide transmission systems. This reflected wave is the result of an impedance mismatch between the isolator section of the system and the unloaded guide section preceding the isolator in the system. When a system component produces a substantial reflected wave, the mismatch may be expressed in terms of a standing wave ratio, which is the ratio of the sum of the magnitudes of incident and reflected waves over their difference. It has been found that prior field displacement isolators, scaled to four kilomegacycles, have standing wave ratios exceeding system limits. By increasing the strength of the applied external field, the standing wave ratio can be lowered considerably, but only at the expense of a sharply reduced magnitude of reverse loss at the lower end of the frequency band.

It is therefore a more specific object of this invention to raise the reverse loss of a field displacement isolator while simultaneously maintaining an acceptable standing wave ratio.

In accordance with the present invention, applicant has discovered that the reverse loss performance of a conventional field displacement isolator is markedly improved by the introduction of an electrically reciprocal dielectric medium of moderate dielectric constant into the field pattern of the displaced waves. The resulting dielectric compensated isolator structure meets not only normal system reverse loss requirements but normal standing wave ratio requirements as well. The dielectric medium, being in the vicinity of the electric field null for the forward propagation direction, has little effect on the transmission characteristics of waves propagating in the forward direction.

In accordance with the principal embodiment of the invention, the dielectric compensating medium takes the form of a thin slab or vane of a solid dielectric material which is positioned longitudinally contiguous to the resistance member to sandwich the resistance member between the dielectric slab and the gyromagnetic element. When the gyromagnetic element is magnetized and electromagnetic waves are applied to the isolator structure, the wave field pattern is displaced in one sense relative to the gyromagnetic element for the forward propagation direction and in an opposite sense relative to the element for the reverse propagation direction. The compensating slab preferably presents the same permeability and dielectric constant to waves propagating in either longitudinal direction. By choosing the material of the compensating slab to have a low to moderate permeability for both propagation directions and to have a dielectric constant of moderate value, somewhat less than that of the gyromagnetic element, the index of refraction of the compensating slab, which is proportional to the ratio of its permeability and dielectric constant, will be the same for both propagation directions. The dielectric slab therefore will affect wave energy in its vicinity in the same manner for both propagation directions. Such reciprocity is desirable to insure that the tendency of the compensating slab to attract wave energy is reciprocal and thus that the displacement action is controlled by the nonreciprocal gyromagnetic element alone.

The above and other objects of the present invention, its features, its nature, and its various advantages will appear more fully upon consideration of the accompanying drawing and the detailed description thereof which follows hereinbelow.

In the drawing:

FIG. 1 is a partially broken away perspective view of a microwave isolator in accordance with the present invention;

FIG. 2 is a transverse cross sectional view of the isolator of FIG. 1, showing the relative orientation of its loading elements; and

FIGS. 3A and 3B are graphical representations illustrating the improved transmission characteristics of a wave guide isolator in accordance with the invention.

Referring more particularly to the drawing, FIG. 1 is a perspective view of a field displacement isolator in accordance with the present invention, comprising a section of hollow-pipe wave guide **10** including within its rectangular transverse cross section both reciprocal and nonreciprocal elements. Guide **10** comprises pairs of oppositely disposed parallel conductive walls, the wider transverse dimension of which, designated *a* in the drawing, is greater than one-half wavelength but less than one wavelength of the lowest frequency wave energy to be transmitted. Generally, wide dimension *a* is equal to three-quarters of this cut-off wavelength and narrow dimension *b* is equal to one-half of wide dimension *a*. In practice, guide section **10** would be provided with terminal flanges at its ends for convenience in connecting the guide into a wave guide system. In order to make the drawing clearer, however, these terminal flanges are not illustrated.

Extending longitudinally within guide **10** at a location closer to one narrow wall than the other is nonreciprocal element **11** of magnetically polarizable material which exhibits gyromagnetic properties at microwave frequencies. Such materials will be referred to in this specification as gyromagnetic materials, the more completely descriptive phrase given above being implied in all cases. The term gyromagnetic material is employed here in its accepted sense as designating the class of materials having portions of the atoms thereof that are capable of exhibiting a significant precessional motion at frequencies within the microwave frequency, this precessional motion having an angular momentum, a gyroscopic moment, and a magnetic moment. Included in this class of materials are ionized gaseous media, paramagnetic materials, and ferromagnetic materials including the spinel ferrites and the garnet-like yttriumiron compounds. One particular class of gyromagnetic materials suitable for use as nonreciprocal element **11** in the present invention comprises iron oxide combined with a quantity of bivalent metal such as nickel, magnesium, zinc, manganese, or other similar material. As a specific example element **11** may comprise magnesium-aluminum-manganese ferrite prepared in the manner described in United States Patent 2,748,353 which issued to C. L. Hogan on May 29, 1956. The height of element **11** is preferably less than the dimension *b* to improve the impedance match between the loaded and unloaded guide sections and to reduce eddy current losses in the guide walls.

Gyromagnetic element **11** is subjected to a magnetic biasing field directed transverse with respect to the longitudinal axis of the guide and having magnetic field lines parallel to the narrow guide walls. Suitable means for producing the transverse field are positioned around guide **10** in the vicinity of element **11**. For example, as illustrated in FIG. 1, these means may comprise magnet **23** which is mounted on the outside of guide **10** and is supplied by a source **24** with energizing current through windings **25** to establish the desired magnetic field. Variable resistor **26** is connected in series with source **24** to provide flexibility in the selection of the magnetic field strength. Alternatively magnet **23** may be a permanent magnet, or element **11** may itself be permanently magnetized. The strength of the applied field is adjusted to a value which will be more fully set out hereinafter, but which is greater than that necessary to saturate the element but less than that necessary to cause the element to become gyroresonantly lossy. Under the influence of the external magnetizing field, element **11** presents different effective permeability values to wave energy propagating in opposite directions through guide **10**. For one propagation direction, the effective permeability is less than unity and wave energy is therefore repelled by the element. As disclosed in United States Patent 2,834,947 issued to S. Weisbaum on May 13, 1958, the magnetized gyromagnetic element may be so proportioned and so spaced from the conductive guide walls to produce, for the propagation direction in which the effective permeability is less than unity, a transverse field pattern within the guide having a very low electric field intensity component at all times in a plane contiguous to and parallel to that longitudinal surface of element **11** which is closer to the longitudinal axis of guide **10**. In order that the low field intensity in this plane be as nearly a null as possible, it is desirable that gyromagnetic element **11** be transversely spaced unequal but finite amounts from both narrow side walls. For the opposite direction of wave propagation, the effective permeability is greater than unity, and wave energy is therefore attracted by the element. For this propagation direction the electric field intensity component in the plane of the null for oppositely propagating waves is found to have a relatively high value.

Extending transversely adjacent and longitudinally contiguous to element **11** in the plane of the electric field null is electrically dissipative element, or sheet, **12** which may be sprayed on or attached by other means to gyromagnetic element **11**. A particularly desirable configuration for resistive sheet **12** is disclosed in the Weisbaum patent mentioned above, and partially illustrated in the broken away view of FIG. 1. As a typical example, the resistivity of element **12** is in the range of from 80 to 125 ohms/square. Since the resistive element is in the plane of the electric field null for one propagation direction, but in a region of considerable electric field intensity for the opposite propagation direction, dissipative transmission loss in the resistive sheet occurs only for the latter propagation direction. In a practical installation of the field displacement isolator, the electric field null and the resistive sheet would coincide for the forward, or through, transmission direction whereas attenuation would be produced for the reverse transmission direction.

Certain transmission characteristics of resistance sheet field displacement isolators at frequencies between 3700 and 4200 megacycles are illustrated in FIGS. 3A and 3B.

In FIG. 3A, which is a graph of the reverse loss in decibels as a function of the frequency of the applied waves in kilomegacycles, curve **13** shows that the reverse loss for typical prior art resistance sheet field displacement isolators varies between 20 decibels at 3.7 kilomegacycles and 22 decibels at 4.2 kilomegacycles. This curve is given the legend "low field no dielectric." Generally, such a magnitude of reverse loss, if maintained over the transmission band is adequate to meet system specifications. However, at the biasing magnetic field strengths used to produce such reverse loss characteristics over the frequency band of interest, it may be seen from curve **14**, also designated "low field no dielectric," in FIG. 3B that the standing wave ratio for such prior art isolators, as represented by a plot of standing wave ratio versus frequency, does not meet normal system requirements. Thus, the standing wave ratio varies between 1.05 at 3.7 kilomegacycles and 1.12 at 4.2 kilomegacycles, indicating a system performance which is less than desirable.

It has been observed that the system standing wave ratio may be significantly decreased over the transmission band by increasing the magnitude of the external biasing field applied to the gyromagnetic element. Specifically, an increase of the magnetic field strength which produced curve **13** in FIG. 3A when applied to the prior art isolator from 400 gauss to 600 gauss produced curve **15** in FIG. 3B. This curve is designated "high field no dielectric."

Thus, the standing wave ratio has been reduced at both ends of the frequency band and varies between 1.01 and 1.05. Such performance is considered acceptable. However, upon increasing the magnetic biasing field strength to the higher value necessary to meet system standing wave ratio requirements, it was found that the reverse loss characteristics of the prior art isolators were seriously degraded. Curve **16** in FIG. 3A, also designated "high field no dielectric," illustrates that reverse loss under the influence of the higher field strength varies between 11 decibels at 3.7 kilomegacycles and 21 decibels at 4.2 kilomegacycles. Such performance generally fails to meet microwave transmission system requirements.

Accordingly, and in accordance with the present invention, it has been discovered that by positioning a dielectric slab, illustrated in FIG. 1 as element **17**, transversely adjacent the resistive sheet **12**, reverse loss performance across the frequency band of interest may be improved while maintaining an acceptable standing wave ratio. As shown in FIG. 1, dielectric element **17** extends longitudinally within guide **10** at a location contiguous to resistive sheet **12** and is held in place by machine screws **18**. Preferably, element **17** should extend perpendicular to the broad walls and should have a transverse dimension parallel to the narrow walls of guide **10** equal to or slightly greater than that of gyromagnetic element **11**. When the medium filling the remainder of the guide is air, or some material having a dielectric constant similar to that of air, the dielectric slab should have a dielectric constant within the range of 5 to 7. As disclosed in the above-mentioned Weisbaum patent, the resistance sheet **12** should be spaced from the longitudinal ends of the gyromagnetic element **11** in order that a length of gyromagnetically active wave guide exist to establish the electric field null before the dissipating means are encountered. Such a dimensioning of the resistance sheet serves to reduce losses in the forward propagation direction. Likewise, it has been found that the length of the dielectric slab **17** should be less than that of the gyromagnetic element **11** but greater than that of the resistance sheet **12**. Experimentally such a configuration has produced the most desirable transmission characteristics.

FIG. 2 is a transverse cross sectional view of an improved field displacement isolator in accordance with the invention showing the transverse arrangement of the elements **11**, **12**, and **17** within guide **10**. One means for supporting the elements in place is represented by threaded machine screw **18** which extends through aligned apertures in dielectric slab **17**, resistive sheet **12**, gyromagnetic element **11**, polyfoam washer **19**, and one narrow sidewall of guide **10**. The assembly is held in place by threaded nut **20**. At least two machine screw assemblies would be necessary to support the loading elements in a practical embodiment of the invention. An alternative method of support is the use of a polyfoam filler which is cut away to permit the insertion of the gyromagnetic, resistive, and dielectric elements. The polyfoam filler support dispenses with the need for machine screws with their tendency to disturb the propagating waves.

The improved performance of the dielectric compensated field displacement isolator is illustrated in FIGS. 3A and 3B as curves **21** and **22** which are designated "high field with dielectric." Thus, in FIG. 3A the reverse loss at the lower end of the frequency band has been increased by the addition of the dielectric slab from 11 decibels to 23 decibels while at the upper end of the frequency band the reverse loss remains nearly the same as without the dielectric. In FIG. 3B, curve **22** shows that the standing wave ratio remains nearly the same as before compensation but considerably below that obtained at the lowest magnetic biasing field as illustrated by curve **14**. It is instructive to note that the effect of the dielectric compensating slab at the lower end of the frequency band of interest is much more pronounced than its effect at the upper end of the band. Ordinarily the effect of a dielectric slab in the presence of propagating waves is directly proportional to the frequency and, therefore, increases as the wavelength of the waves approaches the physical dimensions of the slab. The effect of the dielectric slab in the embodiments of the invention of FIGS. 1 and 2 is greater at lower frequencies and cannot therefore be explained by the conventional and well-known theory of the dielectric loaded wave guide.

Models of the present invention have been successfully operated over the frequency band from 3.7 kilomegacycles to 4.2 kilomegacycles. In the models, which were assembled in rectangular wave guide having inside dimensions of 2.290 inches by 1.145 inches, transmission results for which curves **21** and **22** on FIGS. 3A and 3B, respectively, are typical, were obtained with a bar of $Mg_{1.2}Al_{.35}Fe_{1.4}Mn_{.10}$ ferrite of 1345 gauss saturation having dimensions of .787 by .280 by 5 inches and spaced away from the nearest sidewall a distance of .135 inch; a resistance strip width of .195 inch and 92 ohms/square resistivity; and a dielectric slab having a dielectric constant of 5.4, a height of .890 inch, a thickness of .054 inch, and a length of 3.75 inches. The strength of the applied magnetic biasing field was 530 gauss.

In all cases it is understood that the above-described arrangement is merely illustrative of the many specific embodiments which can represent applications of the principles of this 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:

A nonreciprocal field displacement isolator comprising in combination a conductively bounded wave guide designed to support electromagnetic waves over a frequency range from 3.7 to 4.2 kilomegacycles, said guide having a longitudinally extending center line and pairs of opposed broad and narrow walls,

an element of gyromagnetic material extending longitudinally parallel to said narrow walls and located within said wave guide transversely closer to one narrow wall than to the other,

a sheet of electrically dissipative material extending longitudinally contiguous with said element disposed on the surface thereof which is parallel to said narrow walls and closer to said centerline,

said sheet having a maximum longitudinal extent less than the longitudinal extent of said element,

means for producing within said guide a voltage standing wave ratio less than 1.05 over said frequency range,

said means comprising a unidirectional magnetic biasing field applied to said element in a direction transverse to said guide and parallel to said narrow walls,

the strength of said field being substantially greater than the strength indicated by frequency scaling from a higher frequency range,

said element and said sheet being further proportioned and disposed so that said sheet is in an electric field null for a first propagation direction and in a region of substantial electric field intensity for a second propagation direction opposite from said first direction,

and means for increasing the transmission loss in said second direction more at frequencies falling in the lower portion of said frequency band than at frequencies falling in the upper portion of said frequency band,

said means comprising a slab of nonmagnetic dielectric material positioned contiguous and parallel to said sheet to sandwich said sheet between said slab and said element,

the longitudinal extent of said slab being intermediate the corresponding dimensions of said element and said sheet, the dielectric constant of said slab being substantially less than the dielectric constant of said element.

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