United States Patent

[11] **3,617,951**

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Campbell, Calif.
[21] Appl. No. **874,815**
[22] Filed **Nov. 7, 1969**
[45] Patented **Nov. 2, 1971**
[73] Assignee **Western Microwave Laboratories, Inc.**
Los Gatos, Calif.
Continuation-in-part of application Ser. No. 777,804, Nov., 1968, now Patent No. 3,555,459.

[54] BROADBAND CIRCULATOR OR ISOLATOR OF THE STRIP LINE OR MICROSTRIP TYPE

26 Claims, 35 Drawing Figs.

[52] **U.S. Cl.** **333/1.1,** 333/24.2
[51] **Int. Cl.** **H01p 1/32,** H01p 5/12
[50] **Field of Search** 333/1.1, 24.1, 24.2, 24.3

[56] **References Cited**

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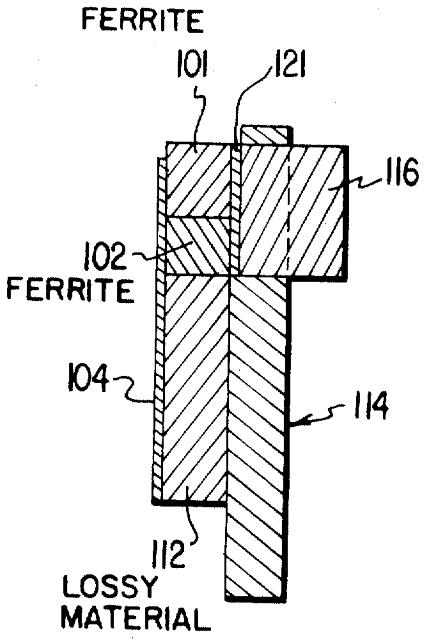
Primary Examiner—Herman Karl Saalbach
Assistant Examiner—Paul L. Gensler
Attorney—Spencer & Kaye

ABSTRACT: A microwave wide band circulator or isolator device of the strip line or microstrip type wherein the circuit is planar and has a plurality of outwardly tapering legs each of which constitutes a port. Ferrimagnetic or gyromagnetic material is provided overlying a substantial portion of the circuit including at least substantially all of the portion thereof functioning as the input and output ports of the device. The energy in the device propagates along the edges thereof, and accordingly the edges are designed to be free of abrupt changes in order that there be no abrupt impedance changes in the circuit. Uniformity of the field within the device utilizing relatively small magnets is achieved by a ground plane structure wherein the portion thereof in contact with the magnet and the gyromagnetic medium is formed from a highly permeable material while the remainder of the ground plane structure is formed from a nonmagnetic material. The peak power handling capability of the device may be increased by utilizing a gyromagnetic medium formed from two different materials chosen for respective optimum forward and reverse propagation characteristics, while the average power handling capability may be improved by means of a unique load structure.



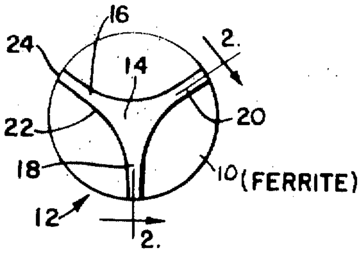


FIG. 1.

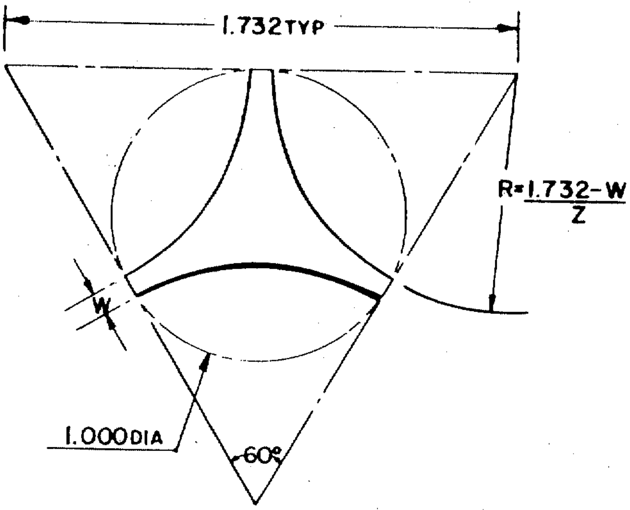


FIG. 2.

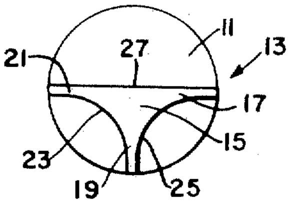


FIG. 3.

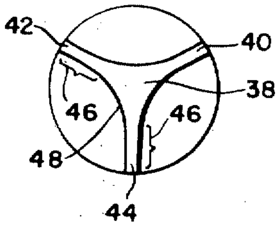


FIG. 4a.

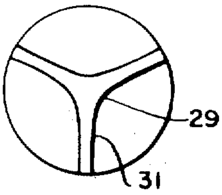


FIG. 4b.

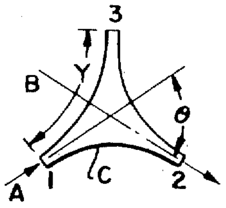


FIG. 5.

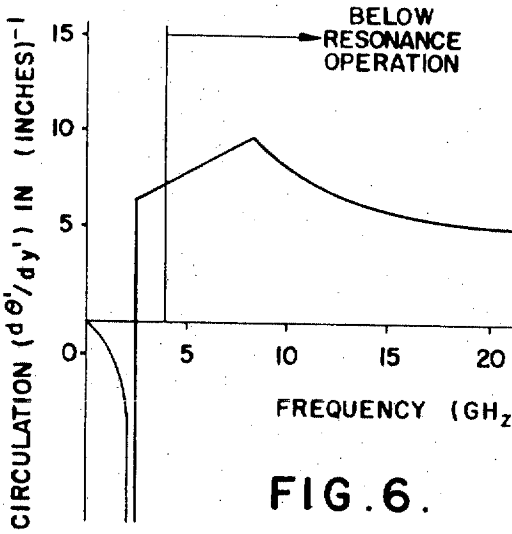
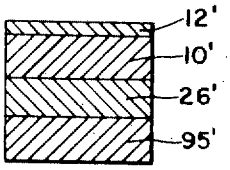


FIG. 6.



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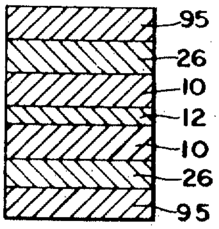

FIG. 7.

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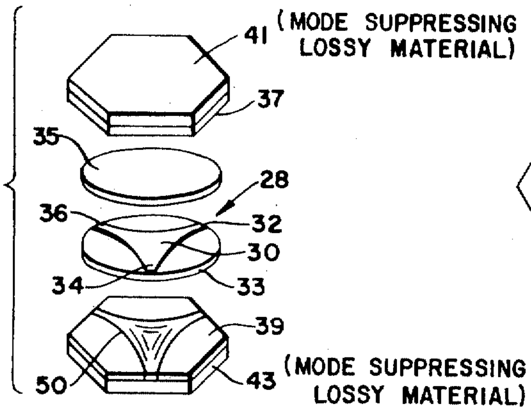


FIG. 9.

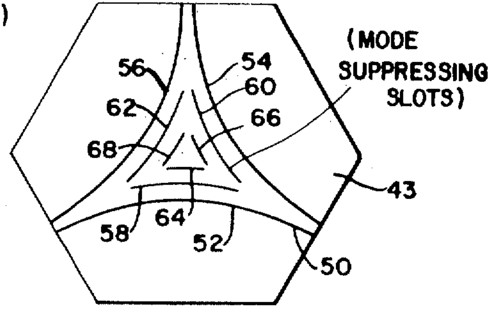


FIG. 10.

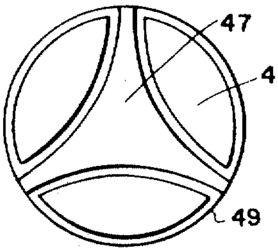


FIG. 11.

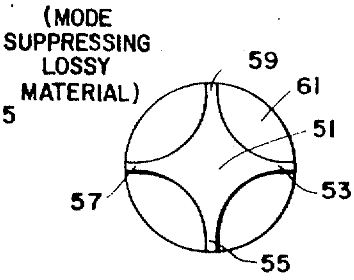


FIG. 12.

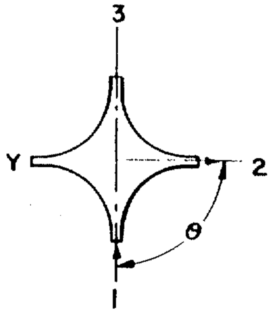
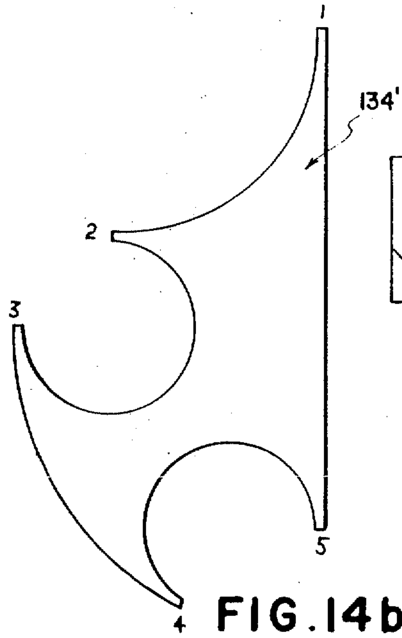


FIG. 13.



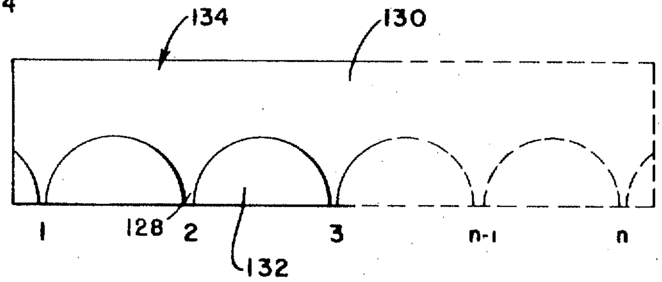


FIG. 14a.

FIG. 14b.

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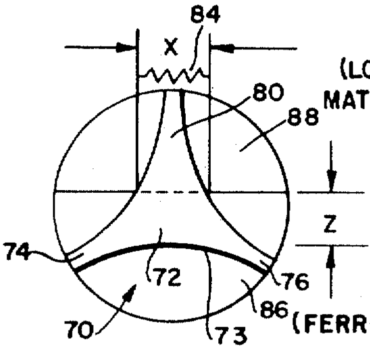

FIG. 15.

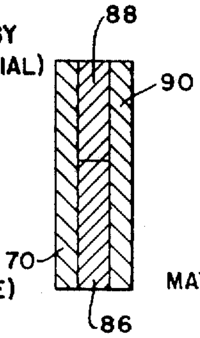

FIG. 16.

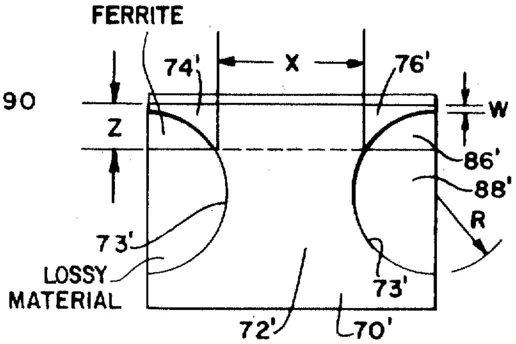

FIG. 17.

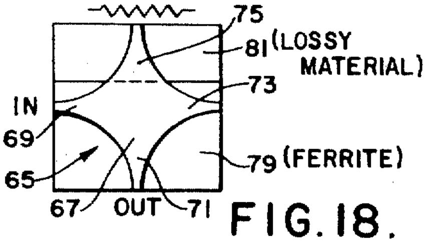

FIG. 18.

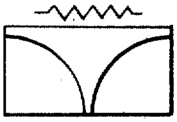

FIG. 19.

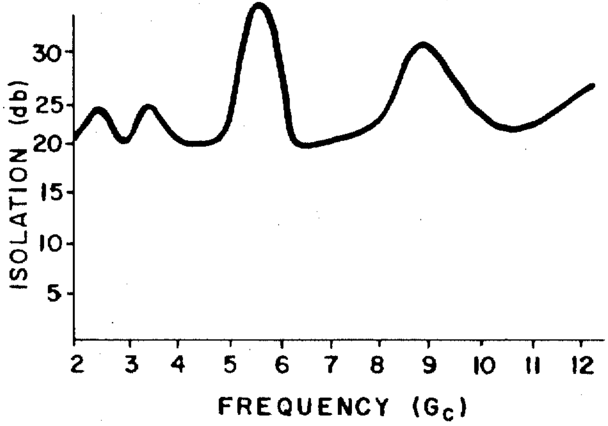

FIG. 21a.

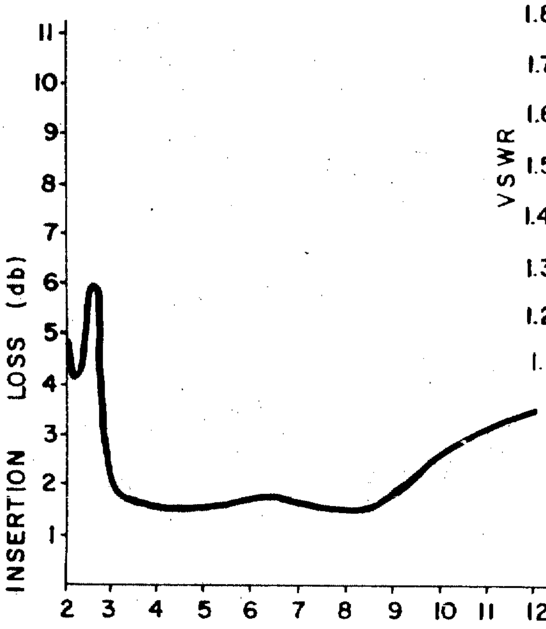

FIG. 21b. FREQUENCY (Gc)

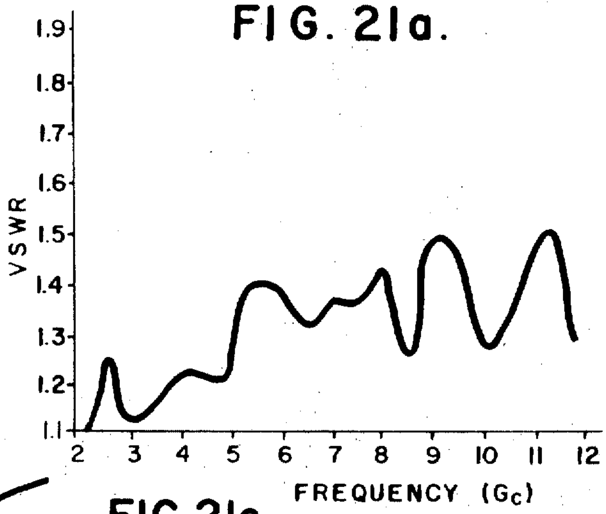

FIG. 21c.

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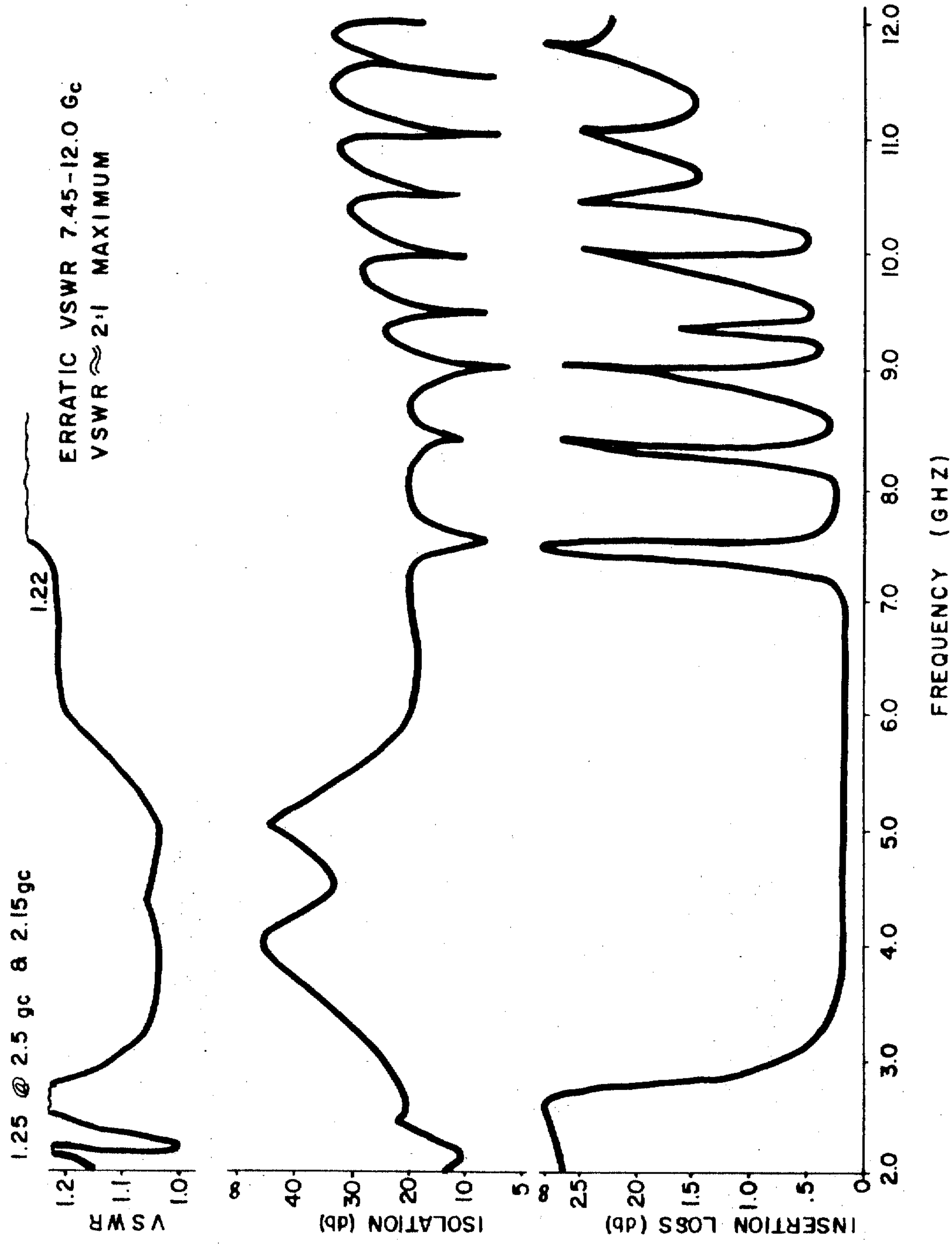

FIG. 20.

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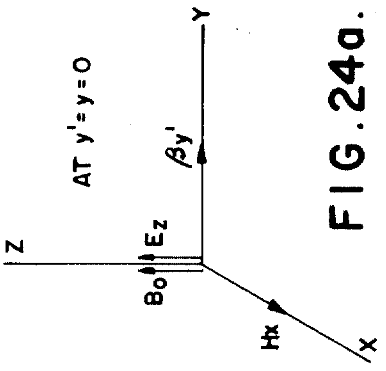

FIG. 24a.

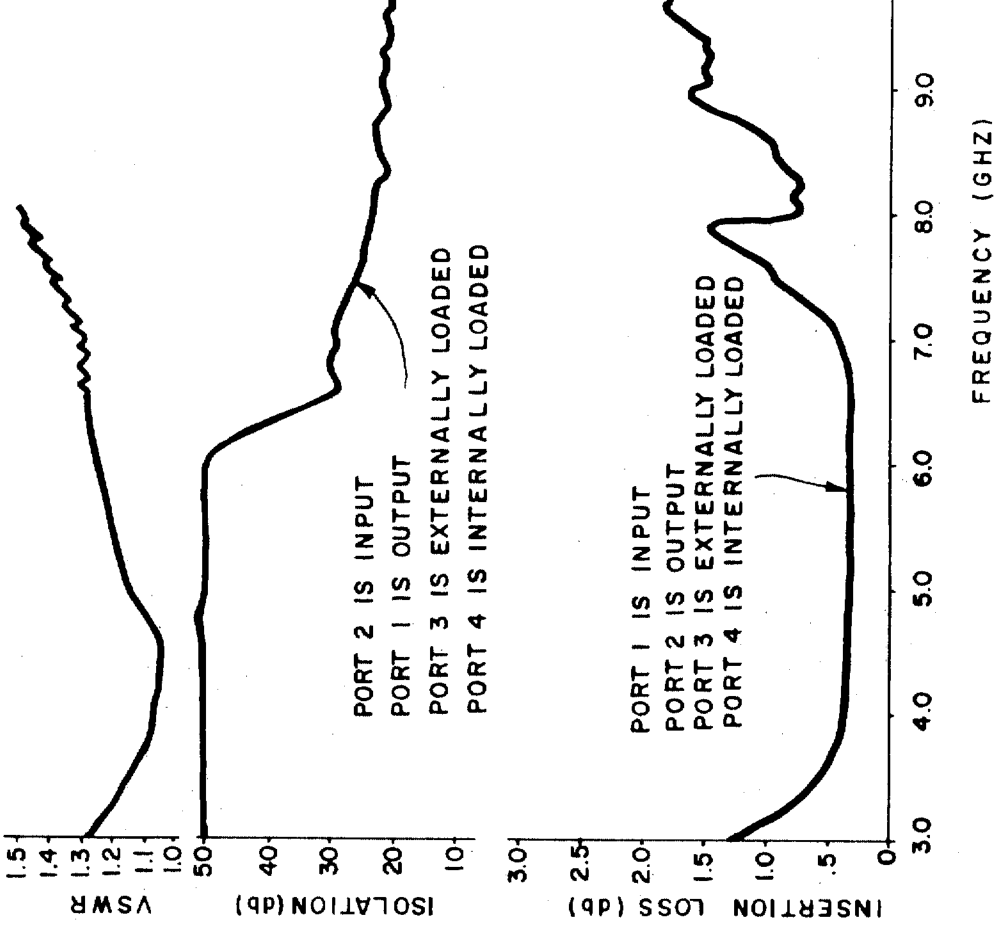

FIG. 22.

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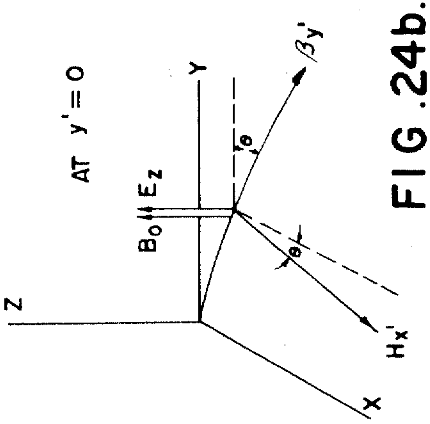

FIG. 24b.

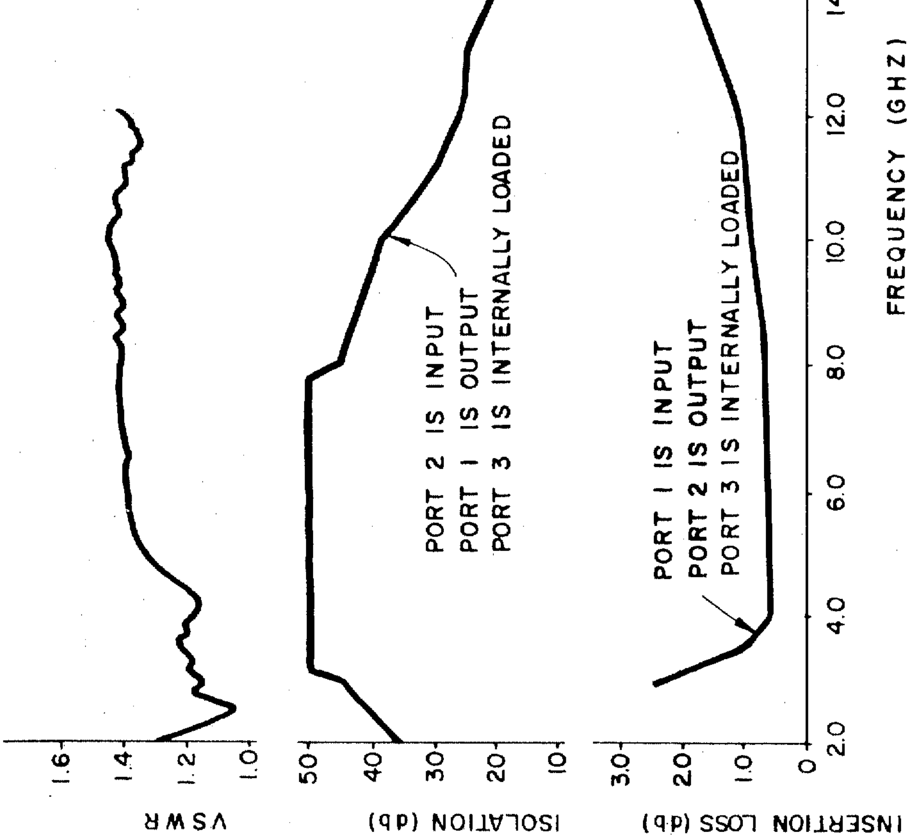

FIG. 23.

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FIG. 25

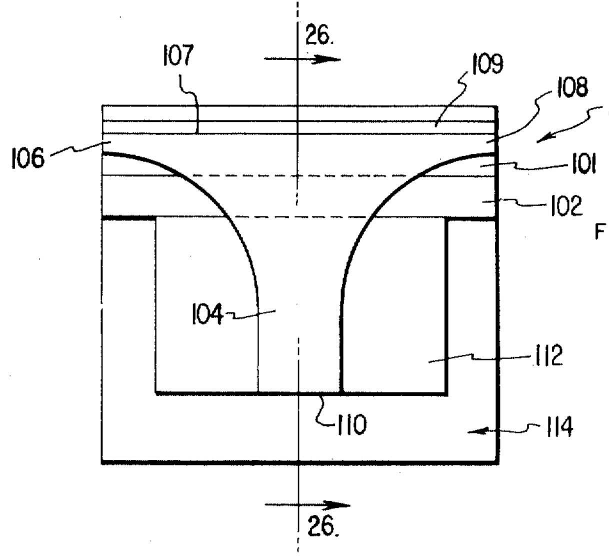


FIG. 26

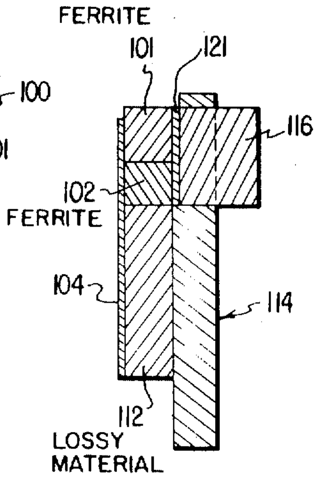


FIG. 28

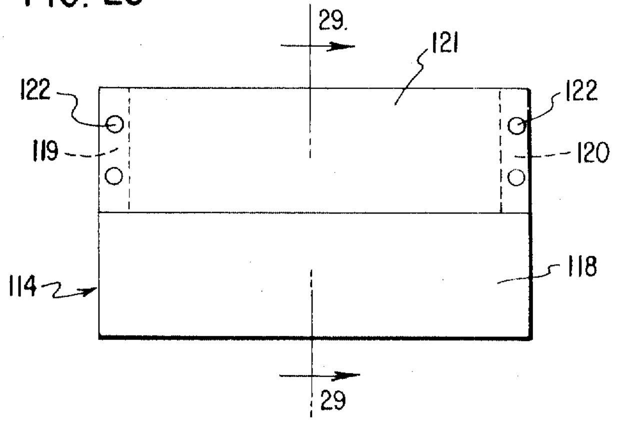


FIG. 29

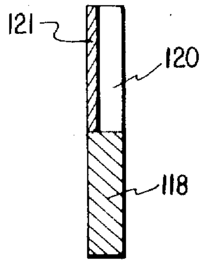
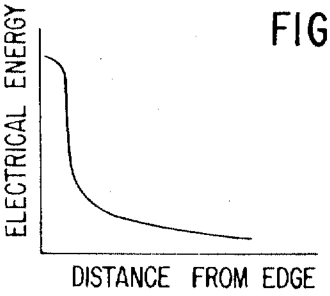


FIG. 27



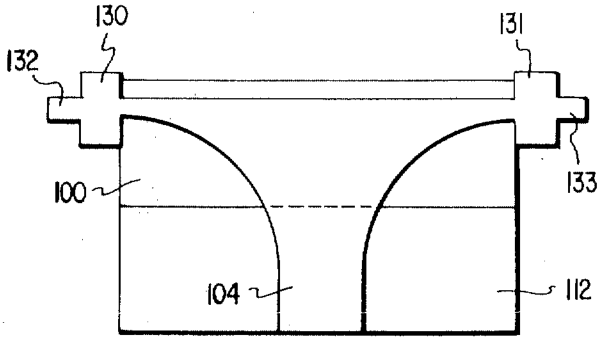


FIG. 30

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BROADBAND CIRCULATOR OR ISOLATOR OF THE STRIP LINE OR MICROSTRIP TYPE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of copending application Ser. No. 777,804 filed Nov. 21, 1968, now U.S. Pat. No. 3,555,459 issued Jan. 12, 1971.

BACKGROUND OF THE INVENTION

The present invention relates generally to the microwave art, and more particularly, to a circulator or isolator which is capable of achieving good performance over a large bandwidth.

For clarification, certain terms used herein are explained below as follows:

"Reduce to acceptable limits," when referring to moding or frequency sensitivity, means that the moding or frequency sensitivity has been reduced to the point where it does not lower the minimum isolation below approximately 18 db.

The circulators and isolators referred to are all magnetized transversely to the direction of energy propagation in the circulators and isolators and all are operated below ferromagnetic resonance.

Whenever "ferrite" is mentioned, it should be taken as any transversely magnetized gyrotropic medium. The word "ferrite" is used because, in most practical cases, the medium used is ferrimagnetic substance such as ferrite or a garnet.

The first strip line circulators were symmetrical, three-port junctions with slabs of ferrites between the circuit and the ground planes. These were then made to operate over the desired band of frequencies by trial and error shaping of the circuit and ferrites. For these first strip line circulators, a bandwidth of 10 percent was considered good.

Later, Bosma[1], Fay and Comstock[2], and others[3] made a partly empirical, partly theoretical analysis of the strip line circulator operated in the below ferromagnetic resonance mode in which the ferrite junction was designed to be a resonant cavity. The loaded Q of this cavity was made as low as possible by lowering the imoedance of the ferrite junction, and then using quarter wave transformers to match this low impedance junction to the input impedance of standard coaxial line—usually 50 ohms. Lowering the impedance of the junction raises the current in the circuit, increasing the coupling to the ferrite, thus lowering the Q of the resonant ferrite junction and increasing the bandwidth. Using a double-step transformer results in a circulator that works over a frequency range of slightly greater than one octave.

The bandwidth of the above device is limited to one octave by, (1) the frequency sensitivity of the ferrite junction and the quarter wave transformers, (2) low field losses beyond the lowest frequency of operation of a given circulator, and (3) moding beyond the highest frequency of operation of a given circulator.

The frequency sensitivity is caused by the fact that the ferrite junction is cavity resonant and the quarter wave transformers are one-quarter wavelength long only at one particular frequency. Thus the circulator will work only in a band of frequencies around the center design frequency.

Low field looses are a result of the inherent properties of the ferrite material commonly used in circulators. For polycrystalline garnet materials, it means that satisfactory operation cannot be achieved in the below ferromagnetic resonance mode of operation below a frequency given approximately by:

$$f_{min} = (2/3\ \%)(4\pi Ms)$$

where

f_{min} =approximate minimum frequency of operation in MHz.

$(4\pi Ms)$ = saturation magnetization of the ferrite in gauss.

γ=gyromagnetic ratio of the ferrite.

Moding occurs beyond the highest frequency of operation because the physical dimensions of the strip line and ferrite junction are large enough at these higher frequencies to propagate modes other than the desired TEM mode, thus disturbing the operation of the circulator.

In addition, the above devices were made only as three-port devices which gave only about 20 db. isolation over a broad band. Previous attempts at making a four-port junction led to devices that showed poor performance (low isolation) and/or narrow bandwidths. Therefore, if a multiport (four or more ports) device was desired or if a larger isolation than about 25 db. was desired over a wide band, it was necessary to connect two or more three-port circulators together, accepting the higher loss and added complication of a device with two or more ferrite junctions.

Therefore, in order to increase the bandwidth, isolation, versatility and otherwise improve the performance of the device, methods have been devised to, (1) eliminate or reduce to acceptable limits the frequency sensitivity of the circulator by using a nonresonant ferrite junction, (2) eliminate or reduce to acceptable values the moding by using a mode suppression technique, or by designing the ferrite junction so that unacceptable moding is not set up, allowing the device to work over a frequency range up to and exceeding two octaves, (3) devise a multiport device from a single ferrite junction which gives 20 db. minimum isolation over a wide band for each added port (i.e., 20 db. for a three-port circulator, 40 db. for a four-port, 60 db. for a five-port, etc.) with little additional loss, (4) by using internal loading, make a device which gives 40 db., 60 db. or more isolation for the internally loaded port.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a wide bandwidth transmission device, such as a circulator which is not frequency sensitive due to the ferrite junction. The ferrite junction includes a circuit, ground plane(s) and slab(s) of ferrite between the circuit and ground plane(s). The maximum bandwidth, limited by low field losses at the low end and moding at the high end, is about one octave.

Another object is to devise a suitable mode suppressor in order to eliminate or reduce moding to acceptable limits at the upper end of the band. Thus bandwidths up to and exceeding two octaves are possible.

Another object is to design a ferrite junction in which undesirable modes are not set up, or are set up at such a low level as not to degrade performance to below acceptable limits.

Another object is to provide a transmission device with three, four, or n ports with additional isolation achieved with each additional port.

Another object is to provide a device in which one or more ports of an *n*-port device are internally terminated in order to increase the isolation obtainable from that port, and also to provide mode suppression.

Another object is to provide a device that is not as sensitive to variations in $4\pi Ms$, as conventional circulators and isolators are.

Another object is to provide a device that is less sensitive to variations in DC magnetic field than in the case for existing devices.

Another object is to provide a device that is less sensitive to changes in temperature which causes change in DC magnetic field and $4\pi Ms$.

Another object is to provide a device in which symmetry is not an important factor.

There is a minimum size ferrite which is necessary for good operation. For the three-port device, the minimum diameter of the ferrite is approximately twice the diameter of the ferrite used in conventional circulators. But since this is a minimum diameter, any large diameter will also work over the same frequency range. Therefore, another object is to provide a device whose physical dimensions can be varied with little effect on the performance of the device.

It is a further object of this invention to provide an improved ground plane structure which results in a uniform magnetic field within the gyromagnetic or ferrite material, without requiring magnets of large physical size.

It is a further object of this invention to provide a device having an improved peak power handling capability without materially sacrificing the other desired characteristics of the device.

It is still a further object of this invention to provide a device having an increased average power handling capability by providing an isolator device with a unique internal load structure.

It is another object of this invention to provide a novel structural arrangement for providing a connection and impedance matching between the external circuitry and the relatively small dimensioned circuitry of the basic device according to this invention.

These objects and others are accomplished in accordance with the preferred embodiments of the invention wherein the inner conductor of a stripline is arranged to have a central portion and legs extending therefrom. The legs are generally tapered and the edges thereof are preferably connected together in a smooth manner. The tapered legs are free of abrupt changes in direction to assure that the rate of change of the edge of the circuit is less than the rate of circulation of a TEM wave in a transversely magnetized ferrite so that no large mismatches occur which increase the frequency sensitivity of the junction and/or deteriorate the isolation.

According to an improved feature of the invention, a substantially uniform field is provided within the gyromagnetic medium by constructing the ground plane substantially from a nonmagnetic conducting material which is provided with a ferromagnetic portion, for example, of cold-rolled steel, which overlies and is in contact with substantially the entire adjacent surface of the gyromagnetic medium. The opposite surface of the ferromagnetic portion of the ground plane is in contact with and coextensive with the surface of a magnet for generating the magnetic field.

According to another feature of the invention, a basic microwave transmission device according to the invention is modified to improve its peak power handling capabilities by providing the gyromagnetic medium with two coplanar portions formed from different materials. The first portion of the gyromagnetic medium overlies the portion of the circuit in which the energy normally flows in a forward direction, with the material therein chosen to have optimum desired bandwidth, peak power limiting and insertion loss characteristics in the forward direction of energy propagation. The second portion of the gyromagnetic medium overlies the reverse energy flow path of the underlying circuit, and is formed of a material chosen to have optimum desired reverse isolation characteristics.

According to another feature of the invention, the average power handling capability of a microwave isolator device constructed according to the basic teaching of the invention is increased by internally terminating a port of the circuit which is located intermediate the input and output ports. The terminated port is provided with a length which is long compared to the wave length of the lowest frequency of operation of the device, preferably at least three times such wave length. The load for the internally terminated port is provided by means of an overlying layer of lossy material which has a good heat transfer characteristic and is capable of withstanding the high temperatures occurring during operation of the device.

According to a further feature of the invention, the ease with which the circuit of the device according to the invention is connected to the external circuitry is greatly increased by providing the circuitry in the form of a printed circuit having further conductive portions extending from the input and output ports of the circuit. The extensions, which are not covered by the gyromagnetic material, accordingly can have surface areas which are relatively larger than those of the input and output ports, and are dimensioned such that the characteristic impedance thereof is matched to that of the external connections.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a plan view of a portion of a strip line or microstrip three-port circulator illustrating a ferrite disc with a planar circuit placed thereon. FIG. 2 is a explanatory view showing the constructions of a circuit.

FIG. 3 is a plan view of a portion of a strip line or microstrip circulator illustrating a ferrite disc with an asymmetrical planar curvilinear circuit placed thereon.

FIG. 4*a* is a plan view of a planar circuit on a ferrite disc in which the edge of each leg is made up of two different curvilinear lines in series.

FIG. 4*b* is a view similar to FIG. 4*a* but wherein each edge of the circuit is constructed of two different curves.

FIG. 5 is a plan view of a three-port planar circuit member constructed in accordance with the present invention and which is shown for explanatory purposes.

FIG. 6 is a plot of $d\theta'/dy'$ against frequency.

FIG. 7 is a vertical sectional view taken through a strip line circulator of the present invention generally along the plane defined by reference line 2—2 of FIG. 1.

FIG. 8 is a vertical sectional view taken through a microstrip circulator of the present invention generally along the plane defined by reference line 2—2 of FIG. 1.

FIG. 9 is an exploded view of a strip line circulator using one form of mode suppressor.

FIG. 10 is an enlarged plan view of one of the ground plane members of FIG. 9, and shows the construction of a mode suppressor.

FIG. 11 is a plan view of a circulator with another type of mode suppressor placed in the plane of but exterior to the circuit.

FIG. 12 is a plan view of a portion of a four-port strip line or microstrip circulator illustrating a ferrite disc with a planar curvilinear circuit placed thereon.

FIG. 13 is a plan view of a four-port planar circuit member constructed in accordance with the present invention and which is shown for explanatory purposes.

FIG. 14*a* is another form of an *n*-port device.

FIg. 14*b* is another, more general form of a multiport device.

FIG. 15 is a plan view of a three-port device with one port internally terminated.

FIG. 16 is a sectional view through the device shown in FIG. 15.

FIG. 17 is another form of three-port device with one port internally terminated.

FIG. 18 is a plan view of a four-port device with one port internally terminated.

FIG. 19 is a plan view of another form of a four-port device with one port internally terminated.

FIG. 20 is a plot of isolation, insertion loss, and VSWR against frequency for a device of the type shown in FIGS. 1 and 7.

FIGS. 21*a*, *b* and *c* are plots of isolation, insertion loss, and VSWR, respectively, against frequency for a device of the type shown in FIG. 9.

FIG. 22 is a plot of isolation, insertion loss, and VSWR against frequency for the device of the type shown in FIG. 18.

FIG. 23 is a plot of isolation, insertion loss, and VSWR for the device of the type shown in FIG. 17.

FIGS. 24*a* and 24*b* are explanatory views.

FIG. 25 is a plan view of a three-port device according to the invention, having one port internally terminated, and which illustrates a modified gyromagnetic medium arrangement and load arrangement for improving the peak power handling and average power handling capabilities respectively of the device.

FIG. 26 is a sectional view through the device of FIG. 25.

FIG. 27 is a curve illustrating a typical field distribution adjacent an edge of the circuit.

FIG. 28 is a plan view illustrating the improved ground plane structure according to the invention.

FIG. 29 is a sectional view through the ground plane structure of FIG. 28.

FIG. 30 is a plan view of a three-port device illustrating an improved manner of connecting the circuit of the device to the external circuitry.

THEORETICAL BACKGROUND OF THE INVENTION

The following contains the theoretical derivation of propagation of a TEM wave in an ideal transversely magnetized gyromagnetic medium. Equation **21** gives the result of this calculation and FIG. **6** is a plot of equation **21** for an idealized ferrimagnetic material having the dielectric constant and 4πMs of yttrium-iron garnet. Equation **21** indicates that for a given 4πMs of a saturated ferrite or other gyromagnetic medium, the TEM wave wants to circulate at a given rate $d\theta'/dy'$ where θ' is the angle of circulation for a given arc length y'. For a given 4πMs, the TEM wave will, if boundary conditions allow it, circulate through θ'. If boundary conditions are applied which allow the TEM wave to circulate only through θ, by designing the circuit with $\theta<\theta'$, most of the energy of the TEM wave will tend to concentrate on the edge of the circuit. The application of this to the present invention will become clearer below.

A TEM wave is incident on a piece of ferrite biased to saturation by a DC magnetic field applied perpendicularly to the direction of energy travel of the TEM wave. The wave is assumed to be constrained to be a TEM wave; that is, only a TEM wave is allowed to propagate in the ferrite. The ferrite is assumed saturated and lossless. The DC magnetic field is in the z direction. At time $t=0$, the direction of propagation of the TEM wave is in the y direction, and its AC magnetic field (H) is in the x direction (see FIGS. **24***a* and **24***b*).

These figures schematically indicate circulation in a transversely magnetized ferrite. When B_y' is perpendicular to the magnetic field Bo (see FIG. **24***a*) the TEM wave circulates θ' degrees when the wave has moved along a curved path of length y'. The manner of calculating θ' and y' is given below. (1)*

* The notation used is similar to that used in reference (4

(1)* $$\bar{H}=\bar{a}_xH \quad \text{at} \quad y=0, \quad t=0$$

Now consider this linearly polarized TEM wave to be made up of two counterrotating, circularly polarized TEM waves rotating not around the direction of propagation, but around the DC magnetic field; that is, the axis of rotation, while moving with the wave, is parallel to the DC magnetic field.

(2) $$\bar{H}^{cw}=(\bar{a}_x-j\bar{a}_y)\frac{H}{2}e^{-jB^{cw}y'}$$

(3) $$\bar{H}^{ccw}=(\bar{a}_x+j\bar{a}_y)\frac{H}{2}e^{-jB^{ccw}y'}$$

* The notation used is similar to that used in reference (4)

(4) $$\text{where } B^{cw}=\omega\sqrt{\epsilon}\sqrt{\mu_{11}-j\mu_{12}}=\omega\sqrt{\epsilon\mu^{cw}}$$

(5) $$\text{and } B^{ccw}=\omega\sqrt{\epsilon}\sqrt{\mu_{11}+j\mu_{12}}=\omega\sqrt{\epsilon\mu^{ccw}}$$

y' is used instead of y in the phase term for a reason which will become apparent shortly.

(6) Now

$$\bar{H}=\bar{H}^{cw}+\bar{H}^{ccw}$$

$$=\frac{H}{2}\left[\bar{a}_x(e^{-jB^{ccw}y'}+e^{-jB^{cw}y'})+j\bar{a}_y(e^{-jB^{ccw}y'}-e^{-jB^{cw}y'})\right]$$

$$=He^{-\frac{j}{2}(B^{cw}+B^{ccw})y'}$$

$$\left[\bar{a}_x\cos\left(\frac{B^{cw}-B^{ccw}}{2}\right)y'-\bar{a}_y\sin\left(\frac{B^{cw}-B^{ccw}}{2}\right)y'\right]$$

This is seen to be a linearly polarized TEM wave that is curving (or circulating) as it is traveling. So y' was used instead of y because the direction of y' is continually changing. The direction of $\bar{H}$ relative to its direction at $y'=0$ is given by

(7) $$\tan\theta'=\frac{H_y}{H_x}=-\tan\left(\frac{B^{cw}-B^{ccw}}{2}\right)y'$$

(8) $$\theta'=\left(\frac{B^{ccw}-B^{cw}}{2}\right)y', \text{ where } y'=\text{arc length}$$

The constraint that the ferrite propagate only TEM waves is very important. Since the wave is TEM and traveling in the y' direction, the only components of the AC magnetic field are H_x and H_y. Therefore,

The wave equation

(9) $$\nabla^2\bar{H}-\nabla(\bar{\nabla}\cdot\bar{H})+\omega^2\epsilon\hat{\mu}\bar{H}=0$$

reduces to

(10) $$\frac{d^2}{dy'^2}\begin{bmatrix}H_x\\H_y\\0\end{bmatrix}+\omega^2\epsilon\begin{bmatrix}\mu_{11}\mu_{12}&0\\\mu_{21}\mu_{22}&0\\0\ \ 0&\mu_0\end{bmatrix}\begin{bmatrix}H_x\\H_y\\0\end{bmatrix}=0$$

(11) $$\bar{\nabla}\cdot\bar{H}=0 \text{ for TEM wave}$$

where

(12) $$\mu_{11}=\mu_{22}=\mu_0\left[1+\frac{\omega_0\omega_M}{\omega_0^2-\omega^2}\right]$$

(13) $$\mu_{12}=-\mu_{21}=j\frac{\mu_0\omega\omega_M}{\omega_0^2-\omega^2}$$

(14) $$\omega_M=(\gamma)(4\pi M_S), \text{ where } (4\pi M_S) \text{ is the saturation magnetization of the ferrite}$$

(15) $\omega_0=\gamma H_0$ where H_0 is the internal field

(16) γ is the gyromagnetic ratio for the ferrite

Substituting equation (2) into (10) we get

(17) $$B^{cw}=\omega\sqrt{\epsilon}\sqrt{\mu_{11}-j\mu_{12}}$$

Substituting (12) and (13) into (17) obtains

(18) $$B^{cw}=\omega\sqrt{\mu_0\epsilon}\left(1+\frac{\omega_M}{\omega_0-\omega}\right)^{1/2}$$

In like manner

(19) $$B^{ccw}=\omega\sqrt{\mu_0\epsilon}\left(1+\frac{\omega_M}{\omega_0+\omega}\right)^{1/2}$$

Now substituting (18) and (19) into (8)

(20) $$\theta'=\frac{\omega\sqrt{\mu_0\epsilon}}{2}y'\left[\left(1+\frac{\omega_M}{\omega_0+\omega}\right)^{1/2}-\left(1+\frac{\omega_M}{\omega_0+\omega}\right)^{1/2}\right]$$

or, in differential form

(21) $$\frac{d\theta'}{dy'}=\frac{\omega\sqrt{\mu_0\epsilon}}{2}\left[\left(1+\frac{\omega_M}{\omega_0+\omega}\right)^{1/2}-\left(1+\frac{\omega_M}{\omega_0+\omega}\right)^{1/2}\right]$$

An important case is when $\omega\gg\omega_0$, ω_M. Then

(22) $$\theta'=\frac{\sqrt{\mu_0\epsilon}\,\omega_My'}{2},\ y'=\frac{2\theta'}{\omega_M\sqrt{\mu_0\epsilon}}$$

or, in differential form

(23) $$\frac{d\theta'}{dy'}=\frac{\omega_M}{2}\sqrt{\mu_0\epsilon}$$

That is to say, for $\omega >> \omega_o, \omega_n$, circulation is independent of frequency. The real part of Eq. (21) is plotted as a function of frequency in FIG. **6**.

FIG. **6** is a plot of equation **21** of the circulation $d\theta'/dy'$ in inches ^{11} against frequency. It is for a TEM wave in a ferrite with fM=5GHz. and $f0$=2.5 GHz. and ϵ=15.2. The ferrite is assumed to be lossless and saturated. The plot is the real part of equation (21). $fM=(2\pi)(\gamma)(4\pi Ms)$.

γ=Gyromagnetic ratio=2.8 MHz/oe for yttrium iron garnet.

$4\pi Ms$ =saturation magnetization = 1,780 oe for yttrium iron garnet.

fo = *ferromagnetic resonant frequency* = γH_o.

H_o = DC magnetic field inside the ferrite.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

With more particular reference to FIG. **1**, a ferrite disc **10** is illustrated with a planar circuit member **12** disposed thereon. The planar circuit member includes a central portion **14** and, in the three-port symmetrical arrangement shown in FIG. **1**, includes three legs **16**, **18** and **20** extending equiangularly therefrom. The edges **22** of the circuit which connect the legs together are curvilinear lines where the curvature is such that $d\theta/dy$ is less than $d\theta'/dy'$ along the entire length of the edge. This requires that the circuit over the ferrite have no abrupt changes in direction, where "abrupt" is considered to mean enough of a change to reduce the isolation of the device to unacceptable values or the make the circuit frequency sensitive such that the isolation or insertion loss deteriorate to unacceptable limits.

Although any curve within the above definition will work, considerable success has been achieved in which the edges of the circuit for the symmetrical three-port circulator are arcs of a circle whose diameter is approximately 1.7 times the diameter of the ferrite disc. An accurate construction of such a circuit is shown in FIG. **2** in which the ferrite disc has a 1 inch diameter. Other lines within the definition of curvilinear are elliptical, hyperbolic, parabolic, or any line within the restrictions listed in the Summary of the Invention, or any combination of these, such as is shown in FIG. **4** and as will be described below. The input impedance of the ferrite junction may be designed to be any convenient value Z_o by using standard stripline or microstrip impedance calculations. Thus, given Z_o, the thickness of the circuit, and the thickness and dielectric constant of the ferrite, the width of the circuit at point **24** in FIG. **1** may be determined.

The input impedance Z_o may be designed to match the impedance of external components or transmission lines, or designed to match the input impedance of a transformer between the ferrite junction and external components or transmission lines.

It should be noted that although a ferrite disc is shown in FIG. **1**, only that part of the ferrite in the vicinity of the circuit and between the circuit and ground plane is utilized for circulation, and the remainder of the ferrite may be any shape, or may be removed.

It should further be noted, that as opposed to conventional ferrite circulators and isolators wherein the ferrite discs utilized overlie only the central or junction portion of the circuit, as indicated in FIG. **1** and all the remaining figures in the application, the ferrite in the device according to the invention overlies substantially the entire circuit, including the legs thereof forming the input and output ports, In particular, for reasons to be more clearly explained below, the ferrite overlies and extends to those edges of the circuit along which the energy is propagated. As more clearly explained with reference to other figures in the application, if one of the ports or legs of the device is internally terminated to constitute a load for the device, then the ferrite need not and does not extend over this portion of the circuit. Preferably, the ferrite extends slightly beyond the edge of the circuit in order to insure that the boundary conditions within the circuit are satisfied.

FIG. **3** shows a portion of a circuit which is asymmetrical and which shows the symmetry is not necessary for good

operation provided the limitations on circuit design mentioned previously, are met. A ferrite disc **11** is provided as is a circuit **13** having a central portion **15** and three tapered legs **17**, **19** and **21**. The circuit **13** is formed of two arcs **23** and **25** and a straight edge **27**. Many other asymmetrical arrangements are possible within the concept of the present invention.

FIG. **4***a* is an arrangement of the circuit member in which a central portion **38** is provided having legs **40**, **42** and **44** extending therefrom. The end portions **46** of the legs are of uniform width. The circuit edges **48** which connect the legs together are arcs of a circle. However, edges **48** and **46** may describe any curvilinear line, and in addition, the edges of the legs may describe more than two curvilinear lines in series, as long as the edges are free of abrupt change in direction, and $d\theta$ is less than $d\theta'/dy'$. FIG. **4***b* shows an arrangement similar to FIG. **4***a* but wherein first curves **29** are used and then second curves **31** are used.

FIG. **5** is a diagrammatic view of a planar circuit of the present invention in which energy is introduced into port **1** in the direction illustrated. The energy now in the ferrite attempts to circulate at a rate of $d\theta'/dy'$ as derived in equation **21** and plotted in FIG. **6**. But the circuit has been designed in which the edge changes direction at the rate of only $d\theta/dy$ * which is less than $d\theta'/dy'$ as specified earlier. Consequently the energy, trying to circulate at a rate greater than the circuit will permit, concentrates on the edge of the circuit. Thus, most of the energy is near the edge and energy decays off in a direction perpendicular to the edge.

Therefore, almost all of the energy introduced into port **1** is transferred to port **2** with only a very little getting directly into port **3**. If the diameter of the ferrite is large enough for a given ferrite $4\pi Ms$ (typically more than twice the diameter of the ferrite used in conventional circulators), the direct energy transfer from port **1** to port **3** is very low, typically much less than 1percent (i.e., greater than 20 db. down). Then most of the energy that does arrive at port **3** comes from the mismatch between the circuit and transmission line at port **2**. This mismatch results from the slight frequency sensitivity of the junction, or from imperfect matching between the ferrite junction and the transformer or transmission line external to the ferrite junction.

In FIG. **7** it can be seen that the stripline arrangement includes the circuit **12**, two ferrites **10**, one disposed on each side of the circuit, and ground planes **26** against the outer surfaces of the ferrites. The biasing magnets **95** are on the outer surfaces on the ground planes **26**.

In FIG. **8** it can be seen that the microstrip arrangement includes the circuit **12'**, one ferrite **10'** placed between the circuit and the ground plane **26'**, and a biasing magnet **95'** located on the ground plane.

The strip line circulator described herein works due to the circulation of a TEM mode. A TEM mode is a transmission line mode in which the electric field, the magnetic field, and the direction of propagation of the wave are mutually perpendicular. (The microstrip circulator works due to the circulation of a transmission line mode similar to a TEM mode.) For the devices described so far, only the TEM mode propagates

*If the edges of the circuit are arcs of a circle as shown in Fig. 2, $\frac{d\theta}{dy}=\frac{\theta}{y}$, where θ and y are defined in Fig. 5, For the circuit of Fig. 2

$$\frac{d\theta}{dy}=\frac{\theta}{y}=\frac{\theta}{2\pi R/6}=\frac{2\pi/6}{(2\pi)(.855)/6}=\frac{1}{.855}=1.17\text{ inch}^{-1}$$

in about the first octave above the low frequency limit set by low field losses. It has been found that beyond the first octave, the device may mode. The frequency where the device starts to mode depends in general on the 4πMs of the ferrite, the applied field, and the change in direction of the circuit ($d\theta/dy$). Once set up, these modes may be trapped and resonate, or, if the ferrite pieces are thick enough, these modes may launch into a parallel plate mode. In either case, the insertion loss and isolation deteriorate to unacceptable values.

However, according to the present invention, these modes can be prevented from forming or those which do form can be absorbed. For the TEM mode, current is in the direction of propagation, but for the TE modes, there are current lines both in the direction of propagation and perpendicular to the direction of propagation. Therefore, if the outer conductor of the strip line is slotted parallel to the TEM mode current flow, current flow for the TE modes will be interrupted, but the current flow of the TEM mode will be only slightly affected. Therefore, by interrupting the current flow of the TE modes, they can be prevented from propagating and the mode in the strip line ferrite device is forced to be TEM.

FIG. 9 is an exploded view of a complete device with a mode suppressor according to the present invention. A circuit member **28** is provided which has a central portion **30** and projecting tapered legs **32, 34** and **36**. Two ferrites **33** and **35** are provided, one on each side of the circuit member. A ground plane **37** is provided at the top of the device and over ferrite **35** and a ground plane **39** is provided adjacent ferrite **33**. Ground plane **37** is a thin layer of conductive material connected to a thicker self-supporting layer of a lossy material **41** and ground plane **39** is connected to a similar material **43**. Both of the ground planes are provided with slots **50** which extend through the ground plane itself and thus the slots in the ground planes **37** and **39** extend all the way through to the lossy material **41** and **43**. These slots can be formed by using well-known etching techniques. However, if desired, only one of the ground planes can be formed with slots therethrough. Furthermore, if desired, a conventional ground plane member may be used on one side.

This high-loss material **41, 43** is placed behind the slots to absorb any energy which is set up across the slots, for example by TE modes. Thus, as the frequency of operation of such a device is increased, the desired TEM modes are propagated since the slots are formed in the direction of the currents of the TEM mode. However, the currents of other modes, such as TE modes, are at an angle or transverse to the slots and therefore fields set up across the slots by these modes are absorbed by the lossy material, thereby providing a higher possible frequency of operation to the device. This mode suppressor will allow operation up to and exceeding two octaves.

FIG. 10 is a plan view of the ground plane member **43** showing the slots **50** formed therein. While any suitable number of slots can be used, it has been found that the arrangement shown in FIGS. 9 and 10 provides good results. The outer series of slots **52, 54, 56** generally follow the contour of the circuit member itself. The next series of slots **58, 60, 62** are generally parallel to the outer series, located approximately $\lambda/4$ from the outer series, where λ is the wavelength of the highest anticipated operating frequency, as measured in the ferrite. The third series have the same relationship to the second series as the second series have to the first series. The same is true for the fourth, fifth, etc., series until there is no more room. Each slot extends far enough toward the end of the leg to give adequate mode suppression with as little loss as possible to the desired TEM mode. The width of the slots of the mode suppressor is made as small as possible—typically 0.003 inch.

FIG. 11 is a plan view of a circulator with another type of mode suppressor. It comprises pieces of lossy material **45** located in the plane of the circuit **47** and close enough to the circuit to absorb the undesired modes before they can resonate, but as far away as possible from the circuit to minimize the loss in the desired TEM mode. The pieces of lossy material **45** and the circuit **47** are disposed on a ferrite disc **49**.

Mode suppression can also be achieved in an internally loaded circulator or isolator as discussed later.

FIG. 12 is similar to FIG. 1 except that the circuit **51** disposed on ferrite **61** contains four legs **53, 55, 57** and **59**. A similar figure could be shown with five or more legs. Each additional leg will give more than 20 db. additional isolation over a wide band provided that the field decay is designed to be high enough by making the diameter large enough for a given 4πMs, and the mismatch at each port does not exceed 1.2 to 1. A formula may be written for minimum isolation between adjacent ports over a wide band.

Minimum isolation between adjacent ports $=(n-2)(20)$ *db.* where n is the number of ports. The larger n is, the larger is the minimum diameter for the above equation to be true for a given 4πMs.

FIG. 13 shows a four-port device in which the power is entering port 1. The power exiting from port 2 is less than 0.5 db. down from the power entering port 1. The power exiting from port 3 is more than 20 db. down from port 1, and the power exiting from port 4 is more than 40 db. down.

The multiport devices described above operate over about one octave without a mode suppressor and up to or exceeding two octaves with a suitable mode suppressor such as are shown in FIGS. 10 and 11, but adapted for multiport use.

As pointed out earlier, symmetry is not a necessary condition for good operation. Two possible multiport devices are shown in FIGS. 14*a* and 14*b*. The circulator shown in FIG. 14*a* consists of a ferrite slab **132** with a planar circuit member **134** disposed thereon. The planar circuit member includes a central portion **130** with *n* legs, such as leg **128**, extending therefrom. These legs may come out in a straight line along one edge as shown in FIG. 14*a*, or they may come out in any manner along the perimeter of the circuit **134'** such as shown in FIG. 14*b*. Again, the only requirement is that $d\theta/dy$ of the edge of the circuit between adjacent low loss ports is somewhat less than $d\theta'/dy'$. All of these circulators work in the same manner as stated in the description of FIGS. 5 and 12, and 13.

The device of FIG. 14*a* can also be an isolator if the upper portion of ferrite **132** as shown in the Figure is replaced by a lossy material. FIG. 15 is a plan view of a three-port device with one port internally terminated. FIG. 16 is a cross section through a microstrip version of this device. This means that lossy material is placed between the ground planes and the leg of the circuit that would conventionally be terminated in a matched load external to the ferrite junction. A three-port circulator with one port terminated is an isolator.

The circuit member **70** is shown having a central portion **72** and projecting tapered legs **74, 76** and **80**. Leg **74** acts as the input port and leg **76** acts as the output port. The port associated with leg **80** may or may not be terminated in a matched load **84**. A ferrimagnetic material **86** is provided across the input and output ports and across the edge of the circuit **73** joining the input and output ports and extends a distance z beyond this edge **73** toward the center of the circuit. The lossy material **88** is under the remainder of the circuit, i.e., under the remainder of leg **80**. Ground plane **90** is also provided.

If the polarity of the biasing magnetic field is picked such that the power circulates in a counterclockwise manner, most of the power entering at leg **74** leaves at leg **76**. z is chosen such that the power level reaching the lossy material is small enough due to field decay so as not to increase the insertion loss to an unacceptable value.

If power is put into the device at leg **76**, it circulates toward leg **80**, and a considerable portion of this energy is absorbed by the lossy material **88** and the load **84**. The power reaching port **74** from port **76** depends upon, (1) the amplitude of the power going directly from port **76** to port **74** due to incomplete field decay, (2) the power reaching port **74** by way of port **80** because of incomplete absorption at port **80**, and

(3) the power reaching **74** because of moding. The relative phase and amplitude of these powers as they add at port **74** determines the isolation of port **74** from port **76**. This isolation is determined by the frequency of operation, the material parameters of the lossy material and ferrite, $d\theta/dy$ of the circuit, z and x, and the match of the load **84**. In general, everything else being equal, the longer the interaction length x, the higher the isolation. Isolation achievable from internal loading can be designed to be any value up to 60 db. and can be designed to exceed 60 db.

Internal loading also provides mode suppression because the lossy material placed over the circuit absorbs modes that would normally be trapped over the circuit and absorbs them before thy can resonate and deteriorate the performance of the device to unacceptable values.

FIG. **17** shows another form of three-port device with one port internally loaded. The circuit **70'** is disposed over a lossy material **88'** and a ferrite **86'**. The circuit includes a central portion **72'** having legs **74'** and **76'** extending therefrom which legs are formed due to arcs **73'** which are formed in opposite sides thereof. This arrangement is preferred to the one shown in FIGS. **15** and **16** because x can be made arbitrarily long to get arbitrarily high isolation, z is easily adjusted to adjust the loss to an acceptable value, R is also easily adjusted, the input and output are in a line and, most important, the straight line edge of the circuit between ports **1** and **2** sets up only a small amount of molding, and this can be absorbed by the lossy material with very little deterioration of the loss and isolation characteristics of the device.

Any of the devices discussed so far may have one or more ports internally terminated in order to increase the isolation and provide mode suppression. The device shown in FIG. **18** is a four-port device like the one shown in FIG. **12**, except that one port is internally terminated. In figure **18**, the circuit member **65** is shown having a central portion **67** and projecting tapered legs **69**, **71**, **73**, and **75**. A ferrimagnetic material **79** is provided across the major portion of the device including leg **71** and most of legs **69** and **73**. A bulk lossy material **81** is provided across leg **75** and the remainders of legs **69** and **73**.

FIG. **19** is like FIG. **18**, except that the bulk material **81** has been replaced by a resistance card which provides the necessary lossy termination. Figure **20** is a plot of isolation, insertion loss, and VSWR of a strip line version of the three-port device shown in FIG. **1**. The ferrites used were 1.000 inch in diameter and 0.085 inch thick and made of polycrystalline yttrium-iron garnet which has a 4πMs, equal to 1780 gauss (Trans-Tech material number G113). The ground planes were made of silver-plated cold-rolled steel. The circuit was made from a sheet of brass 0.005 inch thick to the dimensions shown in FIG. **2**, where w=0.021 inch in order to have an input impedance of approximately 50 ohms. $d\theta/dy$ for this circuit is 1.17. $d\theta'/dy'$ is greater than 5.00 at all frequencies in the below resonance mode of operation and is therefore much greater than $d\theta/dy$. As can be seen from FIG. **20**, the device had isolation exceeding 20 db. and insertion loss less than 0.5 db. from 3.3 to 6.9 GHz. Above 6.9 GHz., the device modes.

The moding can be eliminated by using a mode suppressor. Therefore, the silver-plated steel ground planes used above were replaced by ground planes containing a mode suppressor like that shown in FIGS. **9** and **10**. The ground planes were made from a metallized lossy material, Emerson and Cummings MF116. The metallization was silver, about 0.001 inch thick. The slots were like those shown in FIG. **10** and were 0.003 inch wide and spaced 0.050 inch. The ferrite and the circuit remained the same as those used above. FIGS. **21** show the isolation (FIG. **21***a*) insertion loss (FIG. **21***b*), and VSWR (FIG. **21***c*) of this device. The insertion loss is now higher than before but the device is now useful over a frequency range exceeding two octaves.

FIG. **22** is a plot of isolation, insertion loss and VSWR of a strip line version of the device shown in Figure **18**. The ferrite used was G113 with dimensions of 2.00 inches × 1.20 inches × 0.062 inch. The lossy material was 2.00 inches by 0.80 inch × 0.062 inch MF116. The circuit was 0.005 thick brass with w=0.015, and R=0.992 inch, where G113 and MF116 are defined above and w and R are defined in FIG. **2**. The ground planes were silver-plated cold-rolled steel. Leg **77** of FIG. **18** was terminated in a matched load, and the data plotted in FIG. **22** is between legs **69** and **71**.

FIG. **23** is a plot of isolation, insertion loss, and VSWR of a strip line version of the device shown in FIG. **17**. The ferrite used was 3.00 inches × 0.50 inch × 0.040 inch G113. The lossy material was 3.00 inches × 0.75 inch × 0.040 inch MF116. The circuit was made from 0.005 thick brass with w=0.010, and R=1.250 inch. The ground planes were from silver-plated cold-rolled steel.

Referring now to FIG. **25**, there is shown a device according to the invention which has been modified according to one aspect thereof to provide an increase peak power handling capability. In general, when designing a microwave circulator or isolator, one attempts to design the device so that it has a wide bandwidth capability, a good isolation and insertion loss ratio over this wide bandwidth, and is stable with temperature. Another desirable characteristic of all such devices is that they have a linear response. This latter characteristic is a source of problems in such devices and in particular in devices operated in the pulse condition. These problems result from the fact that many of the ferrite materials used have a relatively low threshold level for the propagated energy, above which limiting occurs resulting in a nonlinear response. While it is possible to increase the threshold level and hence the peak power handling capability of the device by various techniques, including utilizing different ferrite materials having broader spinwave line width (ΔH_k), such changes generally result in a deterioration of the other desirable characteristics of the device. That is, in the design of conventional ferrite microwave devices, the solution of a limiting problem generally results in sacrificing bandwidth, temperature stability, isolation and/or insertion loss.

According to the theory of operation for the basic device as explained above, the magnetic field within the device is bunched or concentrated along the edges of the circuit, resulting in a low-loss path in what becomes the normally forward direction to the circuit and a high-loss path in the opposite or reverse direction. The field strength with its exponential decay from a maximum value at the edge of the circuit is illustrated in FIG. **27**. From this curve it can easily be seen, that because of the rapid decay of the electrical field with distance from the edge, in order to operate with a linear characteristic, it is not necessary for the ferrite located furthest from the edge to have as high a threshold value as the ferrite located adjacent the edge along which the major portion of the electrical energy is propagated. Accordingly, in order to increase the peak power handling capabilities of the basic circuit described above, as shown in FIGS. **25** and **26**, the gyromagnetic medium or ferrite, indicated generally by the reference numeral **100**, is formed from two separate portions **101**, **102** each of which is formed from a different material. The portions **101**, **102** are substantially coplanar with one another and preferably are secured together by conventional techniques to form a laminate gyromagnetic medium **100**. Located adjacent the ferrite **100** is a circuit **104**, which is of a design very similar to that shown in FIG. **17**, having a pair of outwardly tapering member **106**, **108** which serve as the input and output ports for the device. The gyromagnetic means **100** extends substantially over all that portion of the circuit in which current normally flows either in a forward or reverse direction, and preferably as shown, extends slightly beyond the edges thereof, as indicated by the reference numeral **109**, to insure that the field boundary conditions within the device are satisfied.

The circuit **104** is also provided with a third port **110**, located intermediate ports **106**, **108**, which is internally terminated by means of an underlying portion of lossy material **112** which is coplanar with and abuts against the edge of the gyromagnetic medium **100**. A ground plane **114** is provided adjacent to and in contact with both the gyromagnetic medium **100** and the lossy material **112**. The magnetic field within the device is provided by means of a permanent magnet **116** positioned adjacent to the gyromagnetic medium **100**.

The portion **101** of the gyromagnetic medium **100** is formed from a material which has the optimum desired bandwidth and insertion loss characteristics and will not produce limiting at the peak power levels at which the circuit is to be operated. The portion **101** is positioned relative to the circuit **104** so that it overlies or covers that portion of the circuit which will be carrying the major portion of the current or energy in the forward direction. In the illustrated device this is at least along the upper edge **107** of the circuit. The width of the portion **101** is determined by the amount of peak power to be driven through the device in the forward direction and the desired limiting threshold for the device.

The portion **102** of the gyromagnetic medium **100** is formed from a material having an optimum isolation characteristic in the reverse direction. In general this entails a material having a narrower spinwave line width than the material utilized for the portion **101** and accordingly at high levels of peak power the portion **102** would tend to produce limiting. However, since the purpose of the portion **102** is to produce an increased attenuation through the device in the reverse direction, the limiting produced therein is an enhancing rather than a degrading effect.

By way of example in the types of improved peak power handling capabilities achieved by this modification of the device, utilizing a circuit such as shown in FIG. **25** having a gyromagnetic medium **100** formed from a solid piece of garnet material with a $4\pi Ms$ rating of approximately 1,800 gauss (for example Trans-Tech G113) the limiting threshold for the device was below 75 watts peak power. Modifying the same circuit device so that as shown in FIG. **25** it contained a laminated gyromagnetic medium with the portion **102** formed from the same material as the above, and the portion **101** being formed from a doped garnet material having a $4\pi Ms$ rating of approximately 1,100 gauss, (for example, Trans-Tech G1021) and with the portions **101** and **102** being of equal width, the limiting threshold of the device for peak power operation was increased to nearly 450 watts of peak power. A further increase in the proportion of the total width of the gyromagnetic medium **100** being formed from the material contained in the portion **101** will further increase the peak power handling capability of the device.

The device shown in FIG. **25** differs from that shown in FIG. **17**, in that the internally terminated port and the adjacent lossy material (**110** and **112**, respectively, in FIG. **25**), have been modified in order to improve the average power handling capability of the device. In general, the lossy materials utilized to provide internal terminations and the desired degree of isolation have been materials which exhibit a very high attenuation characteristic. In this manner it has been possible to keep the load relatively short. However, with an increased average power for the device, the temperatures occurring in the load are often greater than the maximum temperatures which the generally used lossy materials are capable of withstanding, resulting in disintegration of or fire in the load and failure of the device. For example, a material used for a high power load is polyiron which has an attenuation characteristic of 80 db. per inch and is capable of withstanding temperatures equal to 260° C., resulting in a typical device of the kind disclosed with an average power handling capability of 50 watts. Since the major portion of the energy absorbed and dissipated by such a load occurs near the interface between the lossy material and the ferrite material, and since such materials do not have a relatively good or high heat transfer characteristic, merely lengthening the load does not produce any appreciable increase in the maximum average power handling capability of the device. In order to increase this average power handling capability, the lossy material, rather than being selected for its optimum absorbing or attenuation characteristics, is chosen such that while being absorbent, it has a good heat transfer characteristic, and is able to withstand the temperature occurring during operation. Since the absorbing characteristics of the material are not optimized, its length must be increased in order that the sufficient desired degree of isolation is provided. One material which has proven to be particularly advantageous for this purpose is silicon carbide such as sold commercially under the trade name Carborundum. In order that there not be any leakage of radiant energy into the surrounding area, the portion of the circuit in contact with the lossy material should have a length which is long in comparison to the wave length of the lowest frequency of operation of the device and preferably at least three times as long. It should be noted that although a blunt load is indicated in the drawings, that if desired a tapered load may equally well be used. The substitution of a load constructed as outlined above for a conventional load is an isolator as shown in FIG. **25** resulted in increasing the power handling capability of the device from 50 to 350 watts.

Another factor influencing the overall operating characteristics of microwave circulators and isolators is the uniformity of the magnetic field within the ferrite material. In general, two basic materials have been used for magnets in ferrite devices. One of these materials is an oriented ceramic, and the other is a metal of aluminum, nickel and cobalt commonly referred to and commercially sold as Alnico. The oriented ceramic type of magnets are generally quite uniform in their magnetic characteristics, but their temperature stability is not as good as that of the Alnico type magnet. On the other hand, due to voids and inherent domain structures in the Alnico material, magnets formed from this material do not always present a uniform magnetic field pattern.

In conventional ferrite devices, either of the stripline, microstrip or waveguide type, the magnets used to produce the magnetic field within the device are positioned adjacent the ferrite in relief cuts formed in the ground plane, normally fabricated from aluminum. Although the aluminum ground plane will not materially alter the uniformity of the field, but rather will allow the field produced by the magnet itself to be applied to the ferrite, satisfactory operation of conventional ferrite devices has been achieved utilizing this arrangement, and any further improvement in the uniformity of the field with such devices does not appear to materially improve the performance of the device. On the other hand, while operating devices constructed and operating according to the basic invention have been produced, it has been found that the performance characteristic of such devices is greatly beneficially affected by the uniformity of the magnetic field within the device.

One method of producing a uniform field within a device is to construct the ground planes entirely of a magnetically soft or permeable material such as cold-rolled steel. While such a ground plane structure would produce the uniform field, in addition to the resulting undesirable increased weight for the device, it would also result in the field being distributed over a much larger area, i.e. the entire surface of the ground plane, thereby requiring relatively large magnets in order to produce the required field strength within the device to properly bias the ferrite material. FIGS. **28** and **29** illustrate an improved ground plane structure of the device of FIG. **25**, which is formed in such a manner that a uniform field can be produced within the device without requiring the use of large magnets.

Referring now to FIGS. **28** and **29**, it can be seen that the ground plane indicated generally by the reference numeral **114** in FIGS. **25** and **26** comprises substantially a plate or sheet **118** of a material having the properties of being a relatively good conductor, nonmagnetic, and the ability to readily dissipate heat, for example aluminum. The portion of the plate which is positioned adjacent the ferrite is removed except for a pair of legs **119**, **120**. A plate **121** of a ferromagnetic material, which is preferably highly permeable, for example cold-rolled steel, is then secured to the legs **119**, **120** for example by means of screws **122**. As can be seen in the figure, the thickness of the legs **119**, **120** is reduced and the thickness of the plate **121** is selected such that the surfaces of the plates **118**, **121** adjacent the circuit are coplanar, whereby the plate **121** constitute a portion of the ground plane. In order to prevent the deterioration, or corrosion, of the ground plane as well as to enhance its electrical conductivity, ferromagnetic plate **121** is preferably plated with a conducting, substantially corrosion resistant material for example, silver or gold.

When the improved ground plane structure illustrated in FIG. **29** is utilized in a device, as indicated generally in FIG. **26**, the ferromagnetic plate **121** is positioned directly in contact with the gyromagnetic medium **100** and is positioned such that their adjacent surfaces are substantially coextensive. The magnet **116**, which fits in the recess formed between the legs **119**, **120**, has one of its surfaces in direct contact with the ferromagnetic plate **121** and substantially coextensive therewith.

The substitution of a ground plane structure as shown in FIGS. **28** and **29** (utilizing aluminum and cold rolled steel for the two portions thereof) for a conventional all aluminum ground plane structure in a ferrite isolator device such as illustrated in FIG. **25** resulted in substantial improvements in the performance thereof, even when using ceramic magnets to properly bias the device. The testing of such a device has shown that the substitution of this improved ground plane structure improved the bandwidth by as much as 15 percent at each end of the frequency range, increased the isolation, decreased the insertion loss to as much as 0.25 db., and improved the temperature stability characteristic.

It should be noted that although the portion **118** of the ground plane is shown as a solid plate, that such a construction is not required. For example, the portion **118** could be formed by providing a layer of a conducting nonmagnetic material, for example, aluminum, on a plate of nonmagnetic, nonconducting material, for example Bakelite by means of plating, depositing, or the like. Of course, with this construction, care must be taken to insure that the conducting nonmagnetic layer has a sufficient skin depth to allow propagation of the energy in the device.

FIG. **30** shows a modification of a circuit device according to the invention whereby ease of connecting the circuit to the external circuitry is improved. With the basic present device described herein, due to the fact that the gyromagnetic medium of ferrite **100** extends substantially to the edge of the circuit, it is necessary that the width of the ports be very narrow in order that the ports be matched in impedance to the external circuitry, for example, the 50-ohm impedance of a transmission line. For example, a normal width for a port would be in the order of 0.010 inch. Such small dimensions render it very difficult and expensive to connect the circuit to the connector. According to the improvements shown in FIG. **30**, the ease in connecting the basic circuit indicated by the reference numeral **104** to the external circuitry, and in particular the connector, is improved by providing the respective ports of the circuit with conductive extensions for example **130**, **131**. Utilizing conventional design techniques, the surface area of the conductive portions **130**, **131** is calculated to provide the desired impedance to provide matching with the external circuitry. Since the portions **130**, **131** are not covered by the ferrite material, and preferably are surrounded by an air dielectric, the surface area (width) thereof in order to match the characteristic impedance of the external circuitry will be considerably larger than that of the circuit at the ports thereof. If required, the portions **130**, **131** may themselves be provided with extensions **132**, **133** of reduced surface area which provide the actual connection points to the circuit connectors; the surface area of the extensions **132**, **133** being proportioned to compensate for any unequal spacing of the point of connection between the ground planes.

It should be understood that all of the embodiments of the invention discussed above which were not specifically shown and described as containing mode suppressors may be constructed with mode suppressors but were not described that way herein for purposes of clarity and to demonstrate that the invention includes such devices without mode suppressors.

It will be understood that the above description of the present invention is susceptible to various modifications, changes and adaptations, and the same are intended to be comprehended within the meaning and range of equivalents of the appended claims.

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I claim:

1. In a microwave transmission device having ground plane means, planar circuit means adjacent said ground plane means and in parallel relation therewith, said circuit means having a plurality of outwardly narrowing tapering members and a shape such that the impedance thereof is free from abrupt changes, gyromagnetic means disposed over a substantial portion of said tapering members, and magnetic field generating means adjacent said ground plane means for magnetically biasing said gyromagnetic means substantially throughout so that said device operates at nonresonance, whereby the energy in said circuit means travels substantially along the edges thereof, the improvement wherein said ground plane means comprises a layer of conducting material having the portion thereof which overlies said gyromagnetic means formed from a ferromagnetic material, and the remainder formed from a nonmagnetic material, said ferromagnetic portion of said ground plane means being adjacent said magnetic field generating means and situated in the magnetic field generated thereby, whereby the magnetic field applied to said gyromagnetic means is uniform.

2. A microwave transmission device as recited in claim 1 wherein said gyromagnetic means extends beyond at least the edge of said circuit along which the energy therein flows in a forward direction.

3. In a microwave transmission device as recited in claim 1 wherein at least one of said tapering members is an input port and at least a second of said tapering members is an output port and wherein said gyromagnetic means overlies the entire surface of said tapering members forming said input and output ports, the improvement wherein said circuit means includes further conductive portions extending from said input and output ports, said further portions having surface areas which are relatively larger than those of said input and output ports and proportioned so that the characteristic impedance thereof is matched to that of the external connections, whereby said circuit means may be more easily connected to the external circuitry.

4. A microwave transmission device as recited in claim 1 wherein said gyromagnetic means is disposed over substantially all of the tapered portions of the ones of said tapering members which constitute signal input or output ports for said

device and the entire edges of said circuit means joining adjacent input and output ports.

5. A microwave transmission device as recited in claim 1 wherein said ferromagnetic portion is in contact with said gyromagnetic means.

6. A microwave transmission device as recited in claim 1 wherein said nonmagnetic conducting portion of said ground plane means is formed on the surface adjacent said planar circuit means of a nonmagnetic, nonconducting plate, said ferromagnetic portion being mounted within a recess in said plate.

7. A microwave transmission device as recited in claim 1 wherein said field generating means is a permanent magnet, said ferromagnetic portion of said ground plane means is highly permeable and is in direct contact with said gyromagnetic means and said magnet, the contacting surfaces of said magnet, said gyromagnetic means, and said ferromagnetic portion being substantially coextensive.

8. A microwave transmission device as recited in claim 1 wherein said magnetic field generating means is a magnet which is in direct contact with said ferromagnetic portion of said ground plane means along substantially the entire adjacent surface thereof.

9. A microwave transmission device as recited in claim 8 wherein the adjacent surfaces of said magnet and said ferromagnetic portion are coextensive.

10. A microwave transmission device as recited in claim 1 wherein said ferromagnetic portion is highly permeable.

11. A microwave transmission device as recited in claim 10 wherein said ferromagnetic material is formed from cold-rolled steel.

12. A microwave transmission device as recited in claim 10 wherein said ground plane means comprises an aluminum plate containing said ferromagnetic portion.

13. A microwave transmission device as recited in claim 10 wherein said ferromagnetic portion is plated with a conducting substantially corrosion resistant material.

14. A microwave transmission device as recited in claim 11 wherein said ferromagnetic portion is gold plated.

15. In a microwave transmission device having ground plane means, planar circuit means adjacent said ground plane means and in parallel relation therewith, said circuit means having a plurality of outwardly narrowing tapering members and a shape such that the impedance thereof is free from abrupt changes, gyromagnetic means disposed over a substantial portion of said tapering members, and magnetic field generating means adjacent said ground plane means for magnetically biasing said gyromagnetic means substantially throughout so that said device operates at nonresonance, whereby the energy in said circuit means travels substantially along the edges thereof, the improvement wherein said gyromagnetic means has first and second coplanar portions formed from different materials, said first portion overlying the portion of said circuit means through which the energy in said circuit means normally flows in a forward direction, and said second portion overlying the portion of said circuit containing the reverse flow path for the energy within said circuit means.

16. A microwave transmission device as recited in claim 15 wherein said gyromagnetic means is disposed over substantially all of the tapered portions of the ones of said tapering members which constitute signal input or output ports for said device and the entire edges of said circuit means joining adjacent input and output ports.

17. A microwave transmission device as recited in claim 15 wherein the said material contained in said first portion of said gyromagnetic means is chosen to have the optimum desired bandwidth, peak power limiting and insertion loss characteristics in the forward direction of energy flow, and the said material contained in the second portion of said gyromagnetic means is chosen to have the optimum desired isolation characteristic in the reverse direction of energy flow, whereby the peak power handling capabilities of said device are increased while still maintaining a relatively high reverse direction isolation characteristic.

18. A microwave transmission device as recited in claim 17 wherein one of said tapering members is an input port and a second of said members is an output port; said circuit means having a third member extending outwardly from a portion of said circuit means intermediate said input and output ports, said third member having a length which is long compared to the wave length of the lowest frequency of operation of said device; a layer of lossy material overlying substantially the entire length of said third member in substantially coplanar relationship with and abutting said gyromagnetic means, whereby said layer of lossy material functions as a load for said circuit means; said layer being formed from a material which has a good heat transfer characteristic, and is capable of withstanding the high temperatures occurring during operation of the device; whereby the average power capability of the device is improved.

19. A microwave transmission device as recited in claim 17 wherein the proportion of said gyromagnetic means constituting said first portion thereof is the minimum proportion which will provide the desired peak power handling capability for the device.

20. A microwave transmission device as recited in claim 17 wherein said material contained in said first portion of said gyromagnetic material is a material which has been doped to provide a material having a spinwave line width which is greater than that of the material contained in said second portion.

21. A microwave transmission device as recited in claim 20 wherein the materials contained in said first and second portions of said gyromagnetic means have magnetic saturation value of approximately 1,100 and 1,800 gauss, respectively.

22. A microwave transmission device as recited in claim 17 wherein said device contains an internal load, said load comprising a lossy material overlying a portion of said circuit means adjacent said second portion of said gyromagnetic means.

23. A microwave transmission device as recited in claim 22 wherein said lossy material is in contact and substantially coplanar with said second portion of said gyromagnetic means.

24. In a microwave transmission device having ground plane means, planar circuit means adjacent said ground plane means and in parallel relation therewith, said circuit means having a plurality of outwardly narrowing tapering members and a shape such that the impedance thereof is free from abrupt changes, gyromagnetic means disposed over a substantial portion of said tapering members, and magnetic field generating means adjacent said ground plane means for magnetically biasing said gyromagnetic means substantially throughout so that said device operates at nonresonance, whereby the energy in said circuit means travels substantially along the edges thereof, the improvement wherein one of said tapering members is an input port and a second of said members is an output port; said circuit means having a third member extending outwardly from a portion of said circuit means intermediate said input and output ports, said third member having a length which is at least equal to three wave lengths of the lowest frequency of operation of said device; a layer of lossy material overlying substantially the entire length of said third member in substantially coplanar relationship with and abutting said gyromagnetic means, whereby said layer of lossy material functions as a load for said circuit means; said layer being formed from a material which has a good heat transfer characteristic, and is capable of withstanding the high temperatures occurring during operation of the device; whereby the average power handling capability of the device is improved.

25. A microwave transmission device as recited in claim 24 wherein said lossy material is silicon carbide.

26. A microwave transmission device as recited in claim 26 wherein said gyromagnetic means is disposed over substantially all of the tapered portions of the ones of said tapering members which constitute signal input or output ports for said device and the entire edges of said circuit means joining adjacent input and output ports.