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FERRITE ISOLATOR UTILIZING ALIGNED CRYSTALS WITH A SPECIFIC ANISOTROPY CONSTANT

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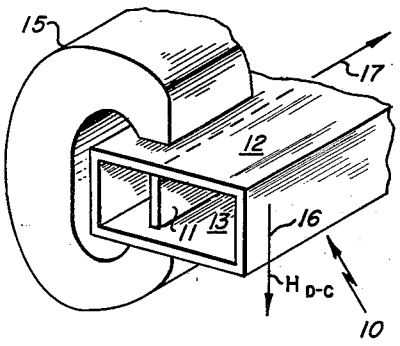


FIG. 1

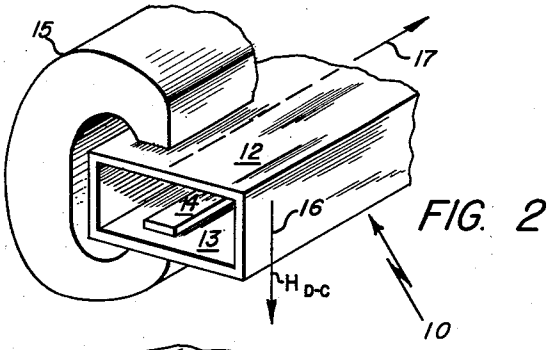


FIG. 2

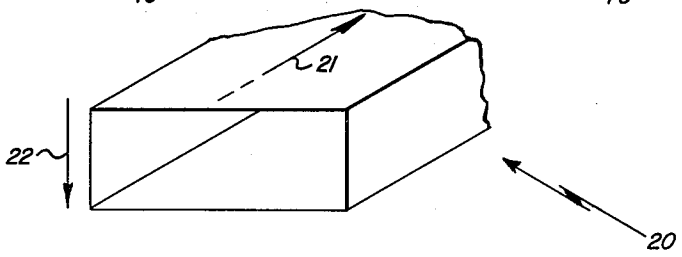


FIG. 3

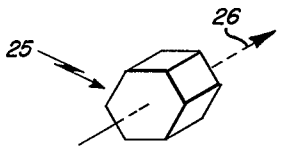


FIG. 3a

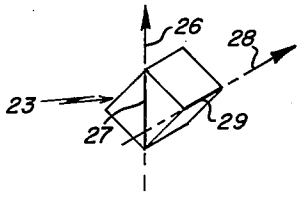


FIG. 3b

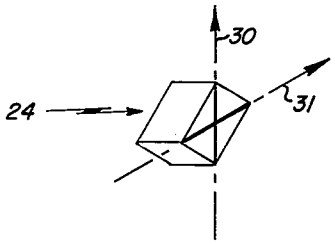


FIG. 3c

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FERRITE ISOLATOR UTILIZING ALIGNED CRYSTALS WITH A SPECIFIC ANISOTROPY CONSTANT

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This invention relates generally to ferrite devices and, more particularly, to the use of grain oriented ferrite materials in a resonance isolator device.

In resonance isolators, it is desirable to obtain a large ratio of reverse attenuation to forward attenuation so that more effective isolation can be maintained in a microwave system. Large ratios have been attained in the past only at the sacrifice of bandwith. If the bandwidth B is defined as that frequency range over which the reverse to forward attenuation ratio R is at least one-half of its maximum value, it can be shown that the maximum reverse to forward ratio is inversely proportional to the square of the bandwidth. It is, therefore, reasonable to define a figure of merit F of an isolator in accordance with the following formula:

$$F = R_{\max}\frac{B^2}{\omega_o^2}$$

In the above formula F is the figure of merit, R is the reverse to forward attenuation ratio, B, is the bandwidth and ω_0 is the operating frequency of the device, that is the frequency for which R assumes its maximum value.

Bandwidth in a resonance isolator is essentially proportional to the ferromagnetic resonance linewidth of the material used with a constant of proportionality that is a relatively sensitive function of the shape of the ferrite material, its magnetization, the freqency of operation, and the cut-off frequency of the waveguide. Under most conditions the bandwidth is substantially smaller than the resonance linewidth. This invention, however, provides a substantial increase in the bandwidth over that obtained in conventional isolators by utilizing a unique orientation of the crystals of the ferrite material in accordance with the anisotropy characteristics of the material. The invention can provide optimum bandwidth response for either single crystals or for oriented polycrystalline materials. In either case the crystals are aligned so that their magnetization vectors are forced to precess along an ellipsoidal cone which has its major axis perpendicular to the waveguide axis. No isolators known at the present time provide the increase in bandwidth provided by this invention and at the same time provide a maximum reverse to forward attenuation ratio.

In a specific embodiment of the invention, for example, which utilizes a polycrystalline material made of hexagonal crystals, the polycrystalline material is grain-oriented so that the hexagonal axes of the individual crystals are substantially aligned. In order to assure correct orientation in the waveguide, the ferrite material is positioned in the waveguide in such a manner that the aligned hexagonal axes of the polycrystalline material are substantially parallel to and coincide with the direction of the longitudinal axis of the waveguide.

The specific embodiments and the operation of the invention may be more clearly described with reference to the following drawing wherein:

FIG. 1 shows a rectangular waveguide utilizing a ferrite material in accordance with the invention;

FIG. 2 shows an alternative embodiment of a rectangular waveguide utilizing the invention; and

FIG. 3 shows the orientation of various crystalline structures to indicate the alignment of selected axes of

the material with the longitudinal axis of the waveguide and with the direction of the D.-C. magnetic field.

In FIG. 1 there is shown a rectangular waveguide **10** having placed therein a slab **11** of ferrite material. In this figure the ferrite slab is place so as to be perpendicular to the top and bottom walls **12** and **13**, respectively, of waveguide **10**. FIG. 2 shows a waveguide **10** having placed therein a ferrite slab **14** resting on the bottom wall **13** of the waveguide. In FIGS. 1 and 2 magnetic fields are applied as shown by utilizing permanent magnets **15** so as to provide a magnetic field H_{dc} in a direction perpendicular to the top and bottom walls of the guide, as shown by arrows **16**. Arrows **17** show the direction of the longitudinal axis of the waveguide.

By the correct orientation of a single crystal or of a polycrystalline oriented ferrite material, the figure of merit for an isolator using such a material can be optimized so as to provide a maximum reverse to forward attenuation ratio and a maximum bandwidth. The orientation of the crystals should be such that the magnetization vector is forced to precess along an ellipsoidal cone which has its major axis perpendicular to the waveguide axis.

If the crystal, for example, has a hexagonal crystalline structure, this desired effect can be achieved, provided the first order anisotropy constant of the material is negative, if the crystals are oriented in such a way that the hexagonal axis coincides with the waveguide longitudinal axis. This can be shown with the help of FIG. 3 and FIG. 3*a*. In FIG. 3 there is shown diagrammatically a rectangular waveguide structure **20** having a longitudinal axis direction **21** and a D.C. magnetization field direction **22** as shown by arrows. If a material having a hexagonal crystalline structure is used in accordance with either of the configurations shown in FIGS. 1 and 2, it is necessary that the hexagonal axis be aligned with the longitudinal axis **21** of waveguide **20**. This alignment assures that the magnetization vector of the material precesses along an ellipsoidal cone which has its major axis perpendicular to the waveguide axis. FIG. 3*a* shows a piece of hexagonal crystalline material **25** wherein the hexagonal crystals have been aligned within the material so that their hexagonal axes, represented by the arrow **26**, are all substantially parallel to each other.

The crystals as utilized in ferrite slabs **11** or **14** of FIGS. 1 and 2 are cut so that the crystals within the material have their internally aligned hexagonal axes positioned so as to be substantially parallel to the longitudinal axis **17** of the waveguide. It has been found that such a configuration produces a substantial improvement in the figure of merit F over that which may be obtained by using materials whose crystals have not been properly oriented with respect to the longitudinal axis of the waveguide.

As another example of the orientation of the crystalline structures of ferrite materials in accordance with the invention, there is considered here the use of materials having cubic crystalline structures such as those shown in FIGS. 3*b* and 3*c*. In accordance with the invention, in order to provide an optimum figure of merit for materials of this type, it is necessary to substantially align the cubic crystals with respect to both the longitudinal axis direction **21** and the D.C. magnetic field direction **22** of waveguide **20**.

The crystal structure shown in FIG. 3*b*, for example, represents a cubic crystalline material **23** having a positive anisotropy. For this material, it is necessary to align a [110] direction (face diagonal) of the cubic crystal in a direction parallel to the magnetic field direction **22**. For the crystal shown in FIG. 3*b*, a [110] direction is designated by the arrow **26** and corresponds to a face diagonal

27, as shown. In addition, for this material to be aligned for a maximum figure of merit, it is necessary to align a [100] direction (cube edge) of the crystal along a line parallel to the longitudinal axis direction **21** of the waveguide. In the crystal structure shown in FIG. 3*b*, a [100] direction is designated by arrow **28** and corresponds to an edge **29** of the crystal. If the crystals within a material of this nature are so aligned, the magnetization direction of the material is forced to precess in the correct direction for optimum isolation operation.

If a cubic crystalline material having a negative anisotropy is used, it is necessary to align the axes as shown in FIG. 3*c*. In that figure there is shown a cubic crystalline material **24** having a [110] face diagonal direction denoted by arrow **30** which is aligned with the magnetic field direction **22**. In addition, another [110] face diagonal direction denoted by arrow **31** is aligned along the direction of the longitudinal axis **21** of waveguide **20**.

In both cases, for FIGS. 3*a*, 3*b* and 3*c*, the material is originally grain-oriented so that the crystals are substantially aligned with each other within the material along substantially the same direction so that the material may be properly cut to provide a correctly oriented slab for use in the configuration shown with respect to waveguides **10**, as shown in FIGS. 1 and 2.

A theoretical analysis from a mathematical viewpoint offers some insight into the reasons why such a grain-oriented material provides a better figure of merit than that found in previously known non-oriented ferrite materials. The figure of merit for a non-oriented material utilized in a configuration corresponding to FIG. 1 may be expressed in accordance with the following equation:

$$F=\frac{8}{1+\frac{1}{a^2}+\frac{1}{2a^4}+\left(1+\frac{1}{a^2}\right)\frac{2\pi M}{\sqrt{(2\pi M)^2+\left(\frac{\omega_o}{\gamma}\right)^2}}} \quad (1)$$

In the above equation, M is the saturation magnetization, ω_o is the operating frequency, γ is the gyromagnetic ratio and "*a*" may be expressed in accordance with the following equation:

$$a=\sqrt{\left(\frac{\omega_o}{\omega_c}\right)^2-1} \quad (2)$$

where ω_c is the cut-off frequency of the waveguide.

As a particular example, one may consider the case wherein the operating frequency is equal to 2800 megacycles and $2\pi M$ is equal to 1000 gauss. In order to provide desirable single mode operation "*a*" is, for practical purposes, equal to or less than the $\sqrt{3}$. If "*a*" is assumed equal to $\sqrt{3}$ and if ω_o and $2\pi M$ take on the above values, the figure of merit is calculated as approximately 3.5 for a non-oriented material.

The same formula as expressed above for the figure of merit in the configuration of FIG. 1 may be applied to the case of a non-oriented material utilized in accordance with the configuration of FIG. 2 if the term $2\pi M$ is replaced by the term $2\pi MN$ where N is the transverse demagnetizing factor. Hence, Equation 1 for the figure of merit may now be written as:

$$F=\frac{8}{1+\frac{1}{a^2}+\frac{1}{2a^4}+\left(1+\frac{1}{a^2}\right)\frac{2\pi MN}{\sqrt{(2\pi MN)^2+\left(\frac{\omega_o}{\gamma}\right)^2}}} \quad (3)$$

The best figure of merit is obtained when N is very small. Under the same set of conditions given for the example above, the figure of merit for a non-oriented material utilized in FIG. 2 is now calculated as approximately equal to 5.75, or 65 percent larger than the figure of merit for a non-oriented material calculated previously for the geometry of FIG. 1. The major difference between the two geometric situations shown in FIGS. 1 and 2 lies in the fact that in FIG. 2 the free precession of the magnetization vector follows a circular cone while in FIG. 1, the circle is distorted by the transversed demagnetizing field into an ellipse whose major axis lies in the plane of the slab, that is to say, in the direction of propagation along the longitudinal axis of the waveguide.

Since the figure of merit is larger in the so-called H-plane geometry in FIG. 2 than in the E-plane geometry of FIG. 1, it is suggested that a further increase in the figure of merit can be obtained by forcing the free precession of the magnetization vector of a crystalline material to follow an ellipsoidal cone with its major axis oriented to be perpendicular to the direction of propagation. As shown with respect to FIG. 3*a*, this orientation can be obtained with a material having hexagonal crystal structure provided the first-order anisotropy constant is negative. In this case, as explained above, the orientation is such that the hexagonal axis substantially coincides with the longitudinal waveguide axis as shown in FIG. 3*a*. In the case of cubic crystalline structures, the orienttion is such that the direction of the magnetic field H_{dc} coincides with a [110] direction. In addition, if the first order cubic anisotropy constant is positive, a [100] direction is aligned with the longitudinal waveguide axis and, if the first order cubic anisotropy constant is negative, a [110] direction is aligned with the longitudinal waveguide axis. These conditions are shown, respectively, in FIGS. 3*b* and 3*c*.

Analysis of the use of grain-orientation such as that which is obtained by correctly aligning a hexagonal crystalline structure of FIG. 3*a* shows that the figure of merit F can be expressed in accordance with the following equation:

$$F=\frac{8}{1+\frac{1}{a^2}+\frac{1}{2a^4}-\left(1+\frac{1}{a^2}\right)\frac{H_a-4\pi MN}{\sqrt{(H_a-4\pi MN)^2+\left(\frac{2\omega_o}{\gamma}\right)^2}}} \quad (4)$$

In this equation, H_a is defined as the equivalent anisotropy field and the other symbols are as defined above. If $(H_a-4\pi MN)$ is much larger than

$$\left(\frac{2\pi_o}{\gamma}\right)$$

the ultimate figure of merit is equal to:

$$F=16a^4 \quad (5)$$

For the value of "*a*" equal to $\sqrt{3}$, F is calculated to have a theoretical maximum of 144 which is approximately 25 times better than the best previous figure of merit of 5.75, obtained with non-oriented materials. In a practical sense it is difficult to obtain this ultimate figure of merit because the internal magnetic field necessary to produce resonance decreases towards zero as the optimum condition for F is approached. Eventually the field is reduced to such a point where it is not strong enough to magnetize the material. However, as one example of a practicable configuration that can be constructed, let us consider a hexagonal crystalline structure wherein $4\pi M=2000$ gauss, $N=1/20$, $H_a=2000$ oersteds, $F=2800$ megacycles and $a=\sqrt{3}$. For such a configuration the figure of merit is 17. If H_a is made equal to 3000 oersteds and everything else remains unchanged, the figure of merit F is increased to 27.5. Thus, it can be seen that the use of grain-oriented materials provides a figure of merit which allows an optimum bandwidth and an optimum reverse to forward attenuation ratio many times that found with non-oriented materials.

The invention is not to be construed as limited to the specific configurations shown and described above inasmuch as variations within the scope of the invention will occur to those skilled in the art. Hence, the invention should not be limited except as defined by the appended claims.

What is claimed is:

1. In combination, a rectangular waveguide for propagating energy in a direction along the longitudinal axis of said waveguide, a ferrite material positioned within said waveguide, means for applying a D.-C. magnetic field in a selected direction perpendicular to the direction of propagation, said material comprising a plurality of cubic crystals having a positive anisotropy constant, the axes of said crystals being substantially aligned with each other within said material, said crystals being oriented within said waveguide so that a [110] direction of said crystals is substantially parallel to the direction of said applied magnetic field and a [100] direction of said crystals is substantially parallel to the direction of the longitudinal axis of said waveguide.

2. In combination, a rectangular waveguide for propagating energy in a direction along the longitudinal axis of said waveguide, a ferrite material positioned within said waveguide, means for applying a D.-C. magnetic field in a selected direction perpendicular to the direction of propagation, said material comprising a plurality of cubic

crystals having a negative anisotropy constant, the axes of said crystals being substantially aligned with each other within said material, said crystals being oriented within said waveguide so that a first [110] direction of said crystals is substantially parallel to the direction of said applied magnetic field and a second [110] direction of said crystals is substantially parallel to the direction of the longitudinal axis of said waveguide.

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