

Jan. 19, 1960

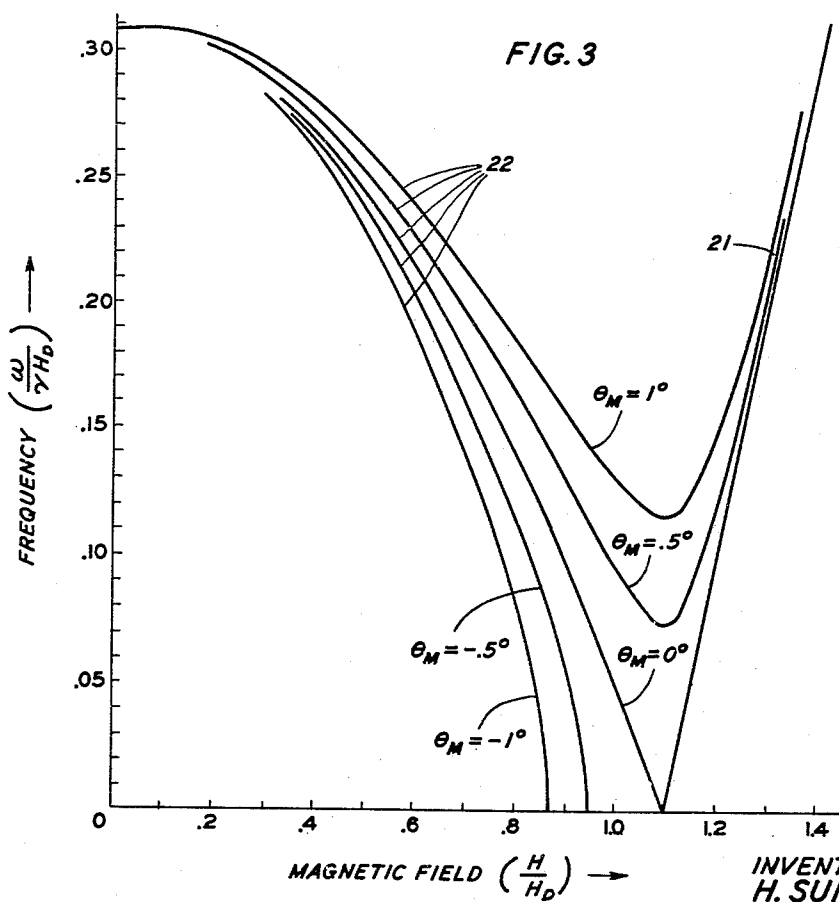
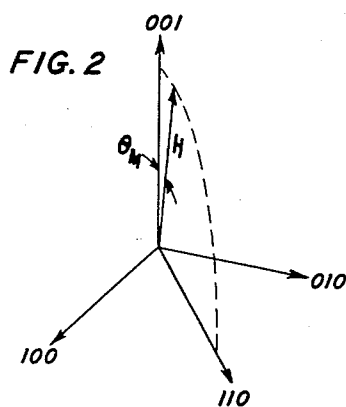
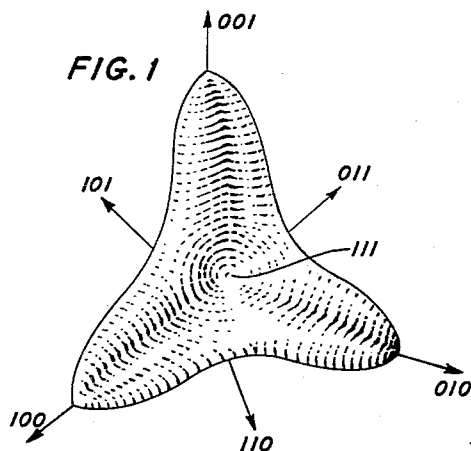
H. SUHL

2,922,125

NONRECIPROCAL SINGLE CRYSTAL FERRITE DEVICES

Filed Oct. 20, 1954

3 Sheets-Sheet 1



INVENTOR
H. SUHL
BY
H. O. Wright
ATTORNEY

Jan. 19, 1960

H. SUHL

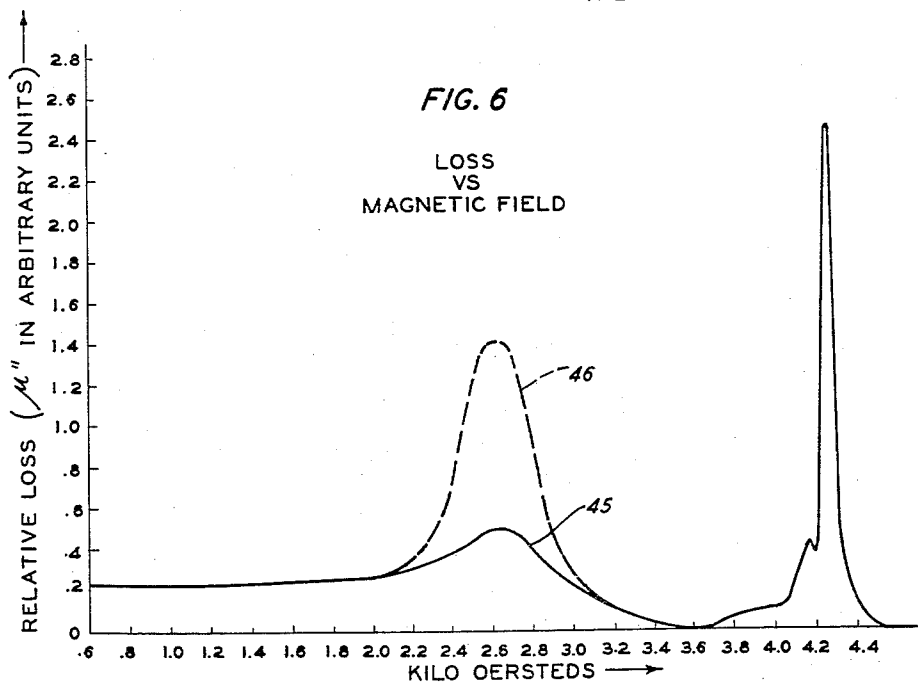
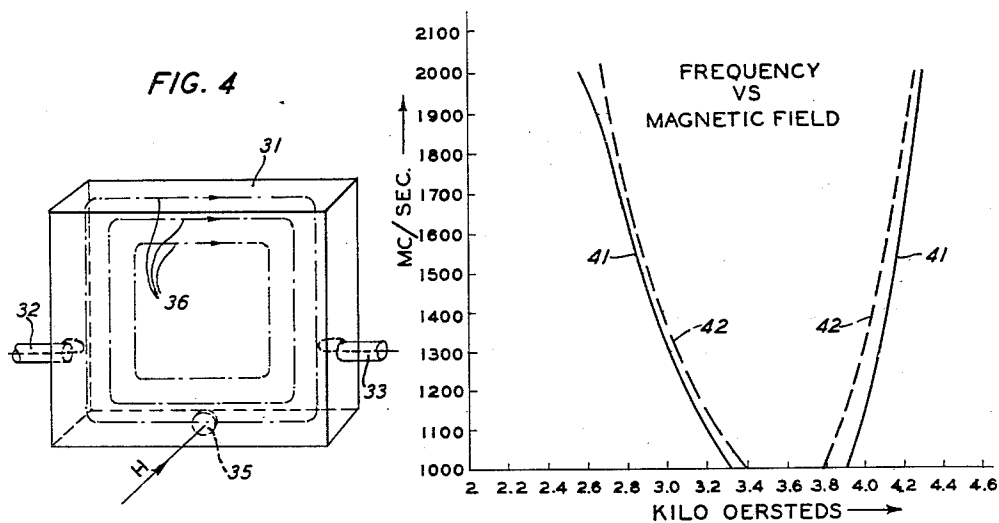
2,922,125

NONRECIPROCAL SINGLE CRYSTAL FERRITE DEVICES

Filed Oct. 20, 1954

3 Sheets-Sheet 2

FIG. 5



INVENTOR
H. SUHL
BY
H. O. Wright
ATTORNEY

Jan. 19, 1960

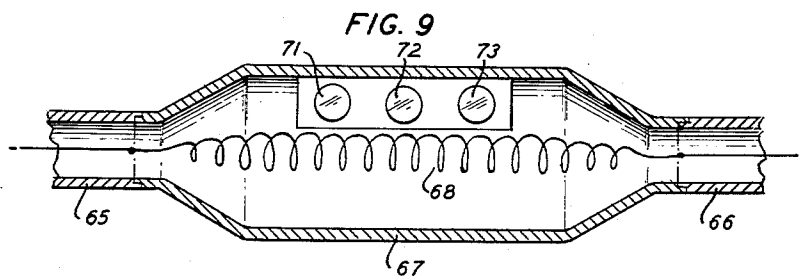
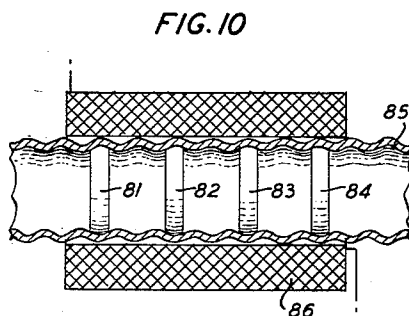
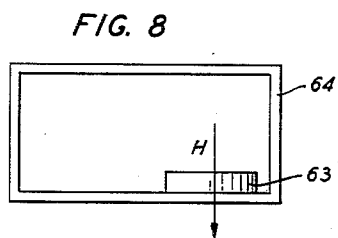
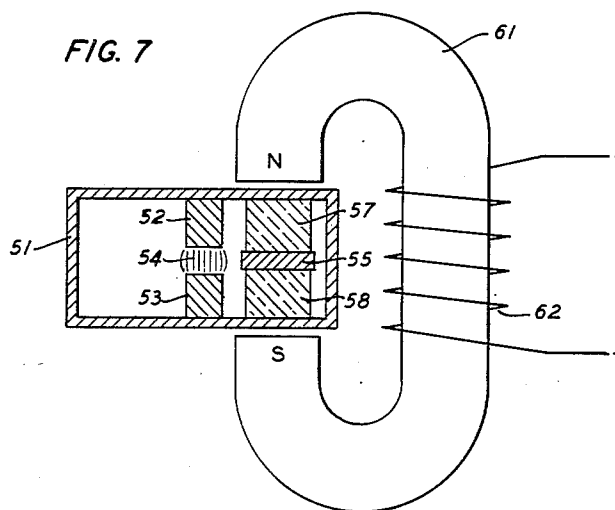
H. SUHL

2,922,125

NONRECIPROCAL SINGLE CRYSTAL FERRITE DEVICES

Filed Oct. 20, 1954

3 Sheets-Sheet 3



INVENTOR
H. SUHL
BY
H. O. Wright
ATTORNEY

1

2,922,125

NONRECIPROCAL SINGLE CRYSTAL FERRITE DEVICES

Harry Suhl, Irvington, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application October 20, 1954, Serial No. 463,466

2 Claims. (Cl. 333-24)

This invention relates to improved nonreciprocal electrical components employing ferrite material. More particularly, it relates to isolators and nonreciprocal phase shifting devices which operate at much lower frequencies than prior art devices using ferrite materials.

It has been proposed heretofore to place a vane of polycrystalline ferrite material off center in a section of wave guide and to apply a transverse biasing magnetic field of considerable intensity to the ferrite vane. When microwaves are applied to the wave guide in one direction at the resonant frequency of the magnetized vane, the microwaves will be greatly attenuated. However, when microwaves are applied to the wave guide in the other direction, little or no attenuation is observed. The wave guide unit thus transmits microwave energy readily in one direction, and attenuates energy transmitted in the other direction. Such devices are known in the art as "isolators."

Although the nonreciprocal wave guide devices employing polycrystalline ferrites biased to resonance are suitable for some purposes, they have several substantial drawbacks. Specifically, these resonance devices have generally been limited to very high frequencies, and require relatively strong magnetic fields. For example, the usual nonreciprocal resonance devices employing polycrystalline ferrites operate satisfactorily only at frequencies above 3,000 megacycles per second, and at biasing magnetic fields of at least several thousand oersteds.

Accordingly, the principal object of the present invention is to very materially reduce the lower limit of the frequency range in which devices using ferrites may be employed.

Another object is to reduce the magnetic field strength required to produce nonreciprocal effects in ferrites.

A collateral object is to reduce the unwanted losses of nonreciprocal electrical components, particularly for use at frequencies below 3,000 megacycles per second.

In accordance with the present invention, it has been discovered that elements cut from single crystals of ferrite exhibit a low frequency resonance characteristic which is not evident in polycrystalline ferrite samples. By properly orienting the single crystal ferrite elements with respect to the biasing magnetic field, resonance may be obtained at much lower frequencies than has been possible heretofore. In addition, through the use of elements made from single crystals of ferrite, the field strength required for both nonreciprocal loss and nonreciprocal phase shift devices is substantially reduced.

Other objects and various advantages and features of the invention will become apparent by reference to the following description taken in connection with the appended claims and the accompanying drawings forming a part thereof.

In the drawings:

Fig. 1 is a diagram of the anisotropy magnetic energy of a single crystal of ferrite exhibiting cubic symmetry;

Fig. 2 is a diagram indicating the deviation of align-

2

ment of the biasing magnetic field from one of the principal crystal axes of a ferrite crystal;

Fig. 3 is a plot of magnetic field required for resonance versus frequency for various amounts of misalignment of the magnetic field as indicated by the diagram of Fig. 2;

Fig. 4 illustrates a resonant cavity having a disc cut from a single crystal ferrite located therein;

Fig. 5 shows plots of resonance frequency versus magnetic field for two different discs made from single crystals of ferrite which were obtained with the cavity of Fig. 4;

Fig. 6 is a plot of loss versus magnetic field strength for a sample cut from a single crystal of ferrite;

Fig. 7 illustrates a vane of ferrite employed as an isolating element in a ridged wave guide structure;

Fig. 8 shows discs of ferrite located asymmetrically in a rectangular wave guide to obtain nonreciprocal effects;

Fig. 9 shows several discs of ferrite which are used with a helix to form an isolator in a coaxial line; and

Fig. 10 shows discs cut from single crystals of ferrite mounted in a corrugated circular wave guide for obtaining Faraday rotation.

In the course of the following specification, a number of single crystal ferrite structures will be discussed which have nonreciprocal properties. Before proceeding to a description of specific structures, however, it is considered that a review of the principles underlying the present invention will be rewarding.

Ferromagnetic resonance in ferrites is not ordinarily observed at frequencies below about 3,000 megacycles. The reason for this is that below 3,000 megacycles, the effective field for resonance must be less than 1,000 oersteds and thus becomes comparable with the anisotropy field which, in general, is of the order of 300 oersteds. The anisotropy field is a property of a single crystal of ferrite which arises from the interaction of internal forces in the crystal. As illustrated by Fig. 1, which shows the anisotropy field of a cubic crystal of ferrite, the anisotropy field has the symmetry of the crystal structure. Unless special arrangements are made, which are to be described hereinafter, the lowest effective internal field that can be attained will be several times the anisotropy field, so that resonance below about 3,000 megacycles is ruled out.

For purposes of analysis, single crystal ferrite elements of ellipsoidal shape will now be considered. It is assumed to form a single domain, whose magnetization will be denoted by the vector M .

The total magnetic energy of the sample will consist of three contributions.

(1) The energy in the applied field H , equal to $-(H \cdot M)$.

(2) The self-energy (i.e., the energy in the demagnetizing field). With respect to the principal axes x, y, z of the ellipsoid this will be $+\frac{1}{2}(N_x M_x^2 + N_y M_y^2 + N_z M_z^2)$ where N_x, N_y, N_z are the demagnetizing factors. This second contribution is closely related to the shape of the ferrite element, in a manner which will be described in greater detail hereinafter.

(3) The anisotropy energy. If the crystal has cubic symmetry, the first approximation to this energy can be written

$$\frac{1}{4}K(M_x^4 + M_y^4 + M_z^4)$$

with the components of M referred to the cube axes x, y , and z , respectively, of the crystal. K is related to the first anisotropy constant k_1 commonly used in the technical literature on ferromagnetic materials as follows:

$$K = -2k_1/M^4$$

where M is the magnitude of M :

$$M^2 = M_x^2 + M_y^2 + M_z^2$$

In the absence of any perturbation, the M vector will point in an orientation in which the total energy E , taken equal to the items (1), (2), and (3) set forth above, has a minimum. If a small perturbation is now applied that displaces vector M from this equilibrium position, a torque will, in general, result, which can be regarded as being due to an effective magnetic field in which M will precess. From the analog of a ball carrying out oscillating motion at the bottom of a dish, one might suppose that the torque, and hence the effective field will be the greater the deeper the minimum; that is, the greater the general curvature of the energy surface near the minimum. On this basis, it would be expected that a small resonant frequency can be obtained if the minimum can be made very shallow; in fact, a "flat spot" in the limit of zero frequency. This corresponds to the low resonant frequency of a small ball rolling back and forth across the bottom of a large shallow dish as contrasted to the high frequency of oscillation of the ball when it oscillates in a small dish having steep sides. The ball-analog is imperfect, however, since we are dealing here with precessional rather than with linear motion. The condition for zero resonant frequency is here most readily derived in spherical polar coordinates θ, φ (in which θ and φ may be considered to designate the "latitude" and "longitude," respectively, of vectors with respect to a principal crystal axis of the crystal), in terms of which:

$$M_x = M \sin \theta \cos \varphi, M_y = M \sin \theta \sin \varphi, M_z = M \cos \theta$$

The total energy E is then a function of θ, φ . The components of the torque along θ, φ in the positive sense, are proportional to

$$\frac{\partial E}{\partial \varphi}, \frac{\partial E}{\partial \theta}$$

respectively. The following equations determine the equilibrium values of θ, φ for zero frequency:

$$\frac{\partial E}{\partial \varphi} = 0, \frac{\partial E}{\partial \theta} = 0$$

For zero resonant frequency, it is also necessary that both components of the torque in a slightly perturbed position $\theta + \delta\theta, \varphi + \delta\varphi$ also vanish. But since

$$\frac{\partial E}{\partial \theta}, \frac{\partial E}{\partial \varphi} = 0$$

the following relationships obtain for zero torque for increasing values of φ :

$$\begin{aligned} \left(\frac{\partial E}{\partial \theta} \right) \delta\theta + \left(\frac{\partial E}{\partial \varphi} \right) \delta\varphi &= \frac{\partial^2 E}{\partial \theta^2} \delta\theta + \frac{\partial^2 E}{\partial \theta \partial \varphi} \delta\varphi \\ &= \frac{\partial^2 E}{\partial \theta^2} \delta\theta + \frac{\partial^2 E}{\partial \theta \partial \varphi} \delta\varphi \\ &= 0 \end{aligned} \quad (I)$$

Similarly, for zero torque in the direction of increasing θ :

$$\frac{\partial^2 E}{\partial \theta \partial \varphi} \delta\theta + \frac{\partial^2 E}{\partial \varphi^2} \delta\varphi = 0 \quad (II)$$

Equations I and II must hold for non-zero values of $\delta\theta, \delta\varphi$. This can be so only if their determinant vanishes:

$$\frac{\partial^2 E}{\partial \theta^2} \frac{\partial^2 E}{\partial \varphi^2} - \left(\frac{\partial^2 E}{\partial \theta \partial \varphi} \right)^2 = 0 \quad (III)$$

This zero resonant frequency condition is a special case of the more general formula giving the resonant frequency near a stationary point:

$$\frac{\omega^2 \text{ res}}{\gamma^2} = \frac{1}{M^2 \sin^2 \theta} \left(\frac{\partial^2 E}{\partial \theta^2} \frac{\partial^2 E}{\partial \varphi^2} - \left(\frac{\partial^2 E}{\partial \theta \partial \varphi} \right)^2 \right) \quad (IV)$$

where γ is the spin gyromagnetic ratio which is commonly used in the technical literature on ferromagnetic materials. Equation III has a geometrical significance. If θ, φ are interpreted as local cartesian coordinates, the form on the left indicates the character of a surface in which the total energy E is constant near the stationary point. The surface is elliptic, parabolic, or hyperbolic near that point according as this expression is greater than, equal to, or less than zero, respectively. The condition for zero frequency is thus that the energy surface be locally parabolic.

Not every stationary point is stable in the sense that small oscillations die out when damping is included in the motion. The condition for stability can be shown to be

$$E_{\theta\theta} \sin^2 \theta + E > 0 \quad (V)$$

Equations III and V indicate that there are many points on the unit sphere such that an applied field of proper magnitude will result in zero resonant frequency. A few specific examples will now be discussed in which symmetry considerations make the computation relatively easy.

The first example is a sphere of a single crystal of a ferrite, such as NiFe_2O_4 , which has cubic symmetry. The principal crystal axes of such a crystal are mutually orthogonal and are identified as the 001, 100, and 010 axes, in accordance with the so-called Miller indices which are commonly employed in the crystallographic art. The principal coordinate planes of the crystal are perpendicular to these axes, and are identified in accordance with the axis with which each is perpendicular. These crystal axes and planes may be readily determined by standard crystallographic procedures using X-rays and a suitable goniometer.

Fig. 1 is a plot of the anisotropy magnetic energy in one octant of a crystal of ferrite having cubic symmetry. It may be observed that the maxima lie along the principal crystal axes 001, 100 and 010; that there are saddle points along the directions 101, 011, and 110; and that there is a minimum in the direction 111, at 45 degrees with each of the principal coordinate planes of the crystal. As an illustration of the use of crystal plane designations mentioned above, the plane through the principal crystal axis 001 and through vectors designated 111 and 110 is designated "(110)." In this designation, the parentheses indicate that the reference is to a plane perpendicular to the direction included in the parentheses, and the bar over the second "1" indicates that the sign of this component of the indicated direction is negative.

The demagnetizing energy for a sphere is constant and thus is of no further interest for the purposes of this first example. Therefore, in the absence of a biasing magnetic field, the M vector will point in the direction 111, which is the direction in which the total magnetic energy has a minimum. This direction 111 is therefore the "easy" magnetization direction.

The effect of applying a biasing magnetic field along crystal axis 001 will now be considered. When the magnetic field $H=0$, the vector M may be aligned with any cube diagonal. For simplicity, we assume that the sphere is a single domain lined up in the direction 111. As the magnetic field H is increased, the vector M will move in the plane through 111, 001 (the (110)-plane), towards axis 001, since the minimum of the total energy E moves towards axis 001. At the same time, the minimum becomes more shallow, all three derivatives in Formula IV decrease steadily, and the resonant frequency therefore decreases. At the same time, the maximum along axis 001 is depressed. Finally, at a certain critical magnetic field strength, maximum and minimum merge, causing a local flat spot at which all three derivatives in Equation IV vanish separately; the resonant frequency

5

is then zero. The equations for this condition in the 110 plane as follows:

$$M_x = M \cos \theta; M_z = M_y = M \frac{\sin \theta}{\sqrt{2}}$$

so that

$$E = -HM \cos \theta + \frac{1}{4}KM^4 \left(\cos^4 \theta + \frac{\sin^4 \theta}{2} \right)$$

The extrema are at

$$\frac{\partial E}{\partial \theta} = 0 = +HM \sin \theta + KM^4 \sin \theta \cos \theta \left(\frac{\sin^2 \theta}{2} - \cos^2 \theta \right)$$

For all values of the magnetic field H , this equation gives $\theta=0$, which describes the maximum, and

$$H = -KM^3 \cos \theta \left(\frac{\sin^2 \theta}{2} - \cos^2 \theta \right)$$

which determines the minimum as a function of H . When H is such that $\theta=0$ solves this equation, maximum and minimum coincide. Then

$$H = H_{crit} = KM^3 = H_a = -\frac{2k_1}{M}$$

where H_a is the "anisotropy field." That the curvature along any longitude is then zero follows from

$$\left(\frac{\partial^2 E}{\partial \theta^2} \right) = HM - KM^4 + 0(\sin^2 \theta) \\ = (H - H_a)M + 0(\sin^2 \theta) = 0 \text{ when } \theta=0$$

That all other second derivatives are likewise zero is intuitively evident. However, Formula IV will now be checked in detail. Because of the fact that derivatives such as

$$\frac{\partial^2}{\partial \varphi^2}$$

are indeterminate at $\theta=0$, it is more convenient to consider the applied magnetic field along the 100 axis

$$\left(\theta = \frac{\pi}{2}, \varphi = 0 \right)$$

The contribution to the energy from this field is then $-HM \sin \theta \cos \varphi$

Thus we find:

$$E = -HM \sin \theta \cos \varphi \\ + \frac{1}{4}KM^4 (\cos^4 \theta + \sin^4 \theta (\cos^4 \varphi + \sin^4 \varphi))$$

$$\frac{\partial E}{\partial \theta} = -HM \cos \theta \cos \varphi \\ + KM^4 \sin \theta \cos \theta (\sin^2 \theta (\cos^4 \varphi + \sin^4 \varphi) - \cos^2 \theta)$$

$$\frac{\partial E}{\partial \varphi} = HM \sin \theta \sin \varphi + \frac{1}{4}KM^4 \sin^4 \theta \sin^4 \varphi$$

Maximum and minimum coincide at

$$\theta = \frac{\pi}{2}$$

$\varphi=0$ if $H=KM^3$, as before. Also

$$\left(\frac{\partial^2 E}{\partial \theta^2} \right)_{\theta=\frac{\pi}{2}, \varphi=0} = HM - KM^4$$

$$\left(\frac{\partial^2 E}{\partial \varphi^2} \right)_{\theta=\frac{\pi}{2}, \varphi=0} = HM - KM^4$$

$$\left(\frac{\partial^2 E}{\partial \varphi \partial \theta} \right)_{\theta=\frac{\pi}{2}, \varphi=0} = 0$$

Thus ω_{res} vanishes when $H=KM^3=H_a$. Incidentally, we have shown that for $H>H_a$, the flat spot at

$$\theta = \frac{\pi}{2}$$

6

$\varphi=0$ becomes a minimum and the resonant frequency becomes

$$\omega_{res} = \frac{\gamma}{M} \sqrt{\frac{\partial^2 E}{\partial \varphi^2} \frac{\partial^2 E}{\partial \theta^2}} \\ = \gamma(H - H_a) \quad (VI)$$

Summarizing, when no biasing magnetic field is applied, the resonant frequency is that which is appropriate to the vector M in its equilibrium position 111. Under these conditions, the above Formula VI shows that the resonant frequency is then γH_a . As the field along a cube axis is increased from zero towards H_a , the resonant frequency drops to zero at $H=H_a$. As the biasing magnetic field H increases beyond H_a , the resonant frequency rises again, and is given by the familiar Formula VI.

In the foregoing example with the magnetic field $H=H_a$ for zero frequency, the stability criterion is only just satisfied

$$(E_{\theta\theta} \sin^2 \theta + E_{\varphi\varphi})$$

The theory for this geometry will thus be incomplete for very low frequencies; large excursions of the M -vector will occur, and the problem will become non-linear. A more desirable location for the applied field is along the 110 direction. At zero applied field, E has a saddle point there, as shown in Fig. 1. Application of a biasing magnetic field in the direction 110 depresses the maximum along the longitude $\varphi=45^\circ$, and deepens the minimum along the latitude $\theta=90^\circ$ (the terms latitude and longitude being employed as though the 001 crystal axis pointed to the north pole). At the same time, the absolute minimum along 111 becomes more shallow and moves towards the direction of the applied magnetic field H . Finally it reaches 110, and creates a flat direction along the longitude, while $E_{\varphi\varphi}$ in the φ -direction has increased, so that the minimum in that direction has deepened. The appearance of the surface near the axis 110 is now that of a parabolic sheet, with $E_{\varphi\theta}=E_{\theta\varphi}=0$. Thus $E_{\theta\theta}E_{\varphi\varphi}-E_{\theta\varphi}^2=0$, so that the resonant frequency is zero. The stability criterion is now satisfied comfortably, since $E_{\theta\theta} \sin^2 \theta + E_{\varphi\varphi} = E_{\varphi\varphi} > 0$.

However, except for certain ferrites (such as cobalt ferrites) having an exceptionally high anisotropy field, the sphere is not a suitable geometry for low-frequency resonance. In practice, the sphere will consist of several domains. To convert it into a single domain, it is necessary to apply sufficient field to sweep out the domain walls. The field needed for this must be such that

$$H - \frac{4\pi}{3}M$$

exceeds zero. This quantity is, very roughly, the field effective for domain wall motion, the anisotropy field being "cancelled" by the exchange field. For zero frequency $H=H_a$. Thus it is necessary that

$$H_a - \frac{4\pi}{3}M > 0$$

a condition which fails for most of the ferrites available at present. For example, in nickel ferrite

$$\frac{4\pi}{3}M \sim 1000 \text{ oersteds}$$

while H_a is only about 240 oersteds. Hence, the lowest frequency attainable in a nickel-ferrite sphere will be

$$\omega \sim \gamma (1000-300)$$

so that

$$\frac{\omega}{2\pi} \sim 2000 \text{ mc./sec.}$$

Another example which will be considered is that of a thin disc cut in the 001-plane, and magnetized along the 001 crystal axis. This case is not very different from the preceding one. The "ellipsoid" now has $N_x=N_y=0$,

7

$N_z=4\pi$, so that the energy now has the following additional "self-energy" or "demagnetizing field" term:

$$-\frac{M^2}{2}4\pi \cos^2 \theta$$

Inasmuch as this term is usually much greater than the anisotropy term, the domains in the unmagnetized disc prefer the direction $\theta=0$, which gives zero demagnetizing energy. Assuming, then, that the sample is a single domain lined up in the 001 plane

$$\left(\theta=\frac{\pi}{2}\right)$$

its orientation within that plane is given by

$$\frac{\partial E}{\partial \varphi}=0$$

that is

$$\varphi=\frac{\pi}{4}$$

(or any equivalent direction). Application of the field, as before, along 001, rotates the M vector towards 001 in the 110-plane. Meanwhile, the minimum becomes more shallow, and ω_{res} decreases. When

$$H=H_D+H_a=H_{\text{crit}}$$

(where $H_D=4\pi M$), zero frequency is reached. Beyond H_{crit} , we again have $\omega=\gamma(H-H_{\text{crit}})$.

In contrast with the previous case, the zero frequency resonant field strength H_{crit} is adequate for the removal of domain walls. The effective internal field for this purpose is $H=4\pi M$. For $H=H_{\text{crit}}$ this makes $H_a \sim 240$ oersteds.

For a third example, a disc cut in the 001 plane will be considered; the magnetizing field may be anywhere in the 010- (or in the 100-) plane. Let θ_H be the angle between H and 001. Then the field H_{crit} required to produce zero frequency is related to θ_H by the following parametric equations (with $H_D=4\pi NM$, $H_a=KM^2$):

$$H_{\text{crit}}^2 = H_a^2 \sin^2 \theta + (H_D + H_a \cos^2 \theta)^2 \cos^2 \theta$$

$$\tan \theta_H = \frac{H_a \sin^2 \theta}{H_D + H_a \cos^2 \theta} \tan \theta$$

The parameter θ is the angle between 001 and M, which in this case is coplanar with H and 001. This case contains that of the sphere as the limit $H_D=0$. Not all orientations of H lead to zero frequency. For example, referring to Fig. 2, if H is located in the 110 plane inclined by a significant angle θ_M to the 001 axis, the energy minimum nearest to it can never be developed into a zero frequency region, no matter what the value of H. However, the other minimum in the 110 plane (the one further removed from H) can become a zero frequency region. The set of curves θ_M relating frequency to field strength required for resonance, which are shown in Fig. 3, illustrate the foregoing principles. For small deviations of the biasing magnetic field H from the 001 axis, it is possible, in practice, to utilize this minimum. As the sample is magnetized, its M vector is in the minimum closest to H. Once it is magnetized, however, it may be rotated so that H, while remaining in the 110 plane, is rotated through 001 over to the "far" side of the vector M. The magnitude of H is then adjusted for zero frequency in accordance with plots $\theta_M = -5^\circ$ or $\theta_M = -1.0^\circ$, as shown in Fig. 3. For moderate inclinations of H to 001, M should remain captured in the minimum which is now the farther of the two from H.

From the equations of motion for small perturbations, it can be shown that the line-width of the resonance at a fixed frequency and for H variable is given by:

$$\frac{\Delta H}{H} = \frac{\alpha \gamma}{MH \frac{\partial \omega_{\text{res}}}{\partial H}} \left(E_{\theta\theta} + \frac{1}{\sin^2 \theta} E_{\varphi\varphi} \right)$$

8

where α is the loss parameter in the Landau-Lifschitz equation; H is the field required for resonance; and ΔH is the distance between the two points on the line profile at which the power absorbed by the sample has declined to

$$\frac{1}{2}$$

This formula shows the importance of alignment for obtaining a narrow absorption line. For a misalignment for which zero frequency cannot be attained, the line-width goes to infinity at the minimum frequency, since $\partial \omega_{\text{res}} / \partial H = 0$ there, while $E_{\theta\theta}$ and $E_{\varphi\varphi} = 0$ stay finite. We note, incidentally, that places where

$$E_{\theta\theta} + \frac{1}{\sin^2 \theta} E_{\varphi\varphi} = 0$$

should give zero line-width if $\partial \omega / \partial H$ is finite. However, such places are "only just" stable, which means that a non-linear analysis of the stability question becomes necessary.

The plots of Fig. 3 and the line-width formula set forth above indicate why low frequency resonance has not been observed in polycrystalline ferrite samples. While the upper branches 21 of the plots θ_M of Fig. 3 are fairly close to each other, the lower branches 22 are widely dispersed even at misalignment angles θ_M of only plus and minus one degree. This confirms the known high magnetic field strength resonance in polycrystalline ferrite samples and explains why the polycrystalline samples with their random crystal orientations do not exhibit a low frequency resonance effect.

Fig. 4 shows a hollow rectangular cavity 31 having input and output coupling structures 32 and 33. A nickel ferrite disc was cut in the 001 plane and mounted near a position of maximum high frequency magnetic field strength, with its plane in the plane of the high frequency magnetic field. The cavity 31 is a flat rectangular conducting box which is operated in the dominant mode. In this mode, the electric field lines extend straight across the narrow dimension of the box. The magnetic field lines 36 form ovals in planes parallel to the large walls of the cavity, as shown by the dashed lines in Fig. 4. The plane of the sample is thus also parallel to the large side walls of the cavity, and the biasing magnetic field is normal to the sample plane, along the 001 direction.

A signal generator having a frequency range extending over the range of the cavity 31 of Fig. 4 was coupled to it at the input connection 32. The output coaxial line 33 was lightly coupled to a crystal detector, and the detected signal displayed on the vertical deflection plates of an oscilloscope, whose horizontal deflection plates were synchronized with the frequency sweep of the generator. Thus a picture of the cavity response was obtained. Resonance was then observed by varying the magnetic field and noting the minima in the response.

Fig. 5 shows the resulting resonant frequency versus steady biasing magnetic field characteristics for two samples, both of 200 mils radius, but with thicknesses 5 mils and 2½ mils, respectively. These curves are limited to frequencies above 1,000 megacycles per second by the lower frequency limit of the cavity of Fig. 4. The solid line curve 41 of Fig. 5 represents the 2½ mil sample and the dotted line curve 42 represents the 5 mil sample. Both curves show the characteristic two arm structure predicted by the theory for this orientation.

Fig. 6 shows the line profile of loss versus magnetic field strength observed at 1,920 megacycles for the 5 mil sample with two different orientations of the 100 axis with respect to the high frequency magnetic field. As the single crystal disc is rotated about its axis, the strength of the absorption of the low field branch varies, while that of the high field branch remains constant. Theory predicts that there should be two absorption maxima for the lower branch as the sample is rotated

in its own plane, and this is confirmed by experiment. The solid line plot 45 represents loss versus magnetic field for one orientation of the disc, and the dotted plot 46 shows an increased low field strength resonance peak for a different orientation of the crystal. Maximum absorption takes place when the high frequency magnetic field is oriented in the $1\bar{1}0$ or $\bar{1}10$ directions.

Proceeding to the consideration of some devices which operate on the principles described hereinabove, Fig. 7 shows a nonreciprocal wave guide structure. The wave guide 51 of Fig. 7 is provided with two opposed conducting ridges 52 and 53 in the broader side walls of the wave guide. These ridges concentrate the electromagnetic wave energy near the gap 54 between the ridges. A thin single crystal of ferrite material 55 is mounted in the wave 51 between two dielectric supporting elements 57 and 58. The ferrite element 55 is located near the gap 54 and is oriented parallel with the broader side walls of the wave guide. With the lines of electric field bridging the gap 54, the circular components of the high frequency magnetic field are concentrated in the region occupied by the ferrite element 55. A biasing magnetic field is applied to the crystal 55 by means of the magnetic core 61 energized by the electromagnet 62.

The circularly polarized components of the high frequency magnetic field rotate clockwise for one direction of propagation through the wave guide section of Fig. 7, and rotate counterclockwise for propagation through the wave guide section in the opposite direction. The magnetic vector M in the ferrite material couples strongly with high frequency magnetic field perturbations rotating in one direction, but is substantially unaffected by perturbations rotating in the opposite direction. Accordingly, there are substantial differences in loss and phase shift characteristics between the two directions of propagation. For example, when the magnetic field is at the resonance value for the frequency of the applied electromagnetic waves, the structure is an isolator. That is, electromagnetic waves applied to the device in one direction are severely attenuated, while electromagnetic waves transmitted in the other direction are affected but slightly. At field strengths other than that required for resonance, the phase shift for the two directions of propagation differs substantially. This phenomenon involving the nonreciprocal characteristics of certain microwave ferrite devices is described in detail in S. E. Miller, application Serial No. 362,193, filed June 17, 1953.

Fig. 8 illustrates a thin element 63 made up of a single crystal of ferrite located on one side of the center line of a rectangular wave guide 64. The device of Fig. 8 operates in substantially the same manner as that of Fig. 7. The magnetic field H is again applied perpendicular to the surface of the ferrite element 63. The only difference between the structure of Fig. 8 and that of Fig. 7 is that the ferrite element is not located at a point where the magnetic field strength is concentrated. While this reduces the nonreciprocal effect to a certain extent, the impedance discontinuity and consequent reflections are also reduced.

In Fig. 9, a nonreciprocal structure for coaxial lines is shown. In this device, the outer conductor of the coaxial line 65, 66 is enlarged at 67 over a substantial length, and the inner conductor is concurrently connected in series with a helix 68. In the region between the helix 68 and the enlarged length of coaxial outer conductor 67, a number of thin discs 71, 72, and 73 are located in a plane through the axis of the conductor structure. These discs are single crystals of ferrite, and have a suitable biasing magnetic field applied perpendicular to their flat surfaces. The nonreciprocal nature of microwave circuits having ferrite material biased as disclosed above and as indicated in Fig. 8 is also discussed in the application of S. E. Miller mentioned hereinabove.

Fig. 10 illustrates a Faraday effect device employing single crystals of ferrite. These single crystals of ferrite 81, 82, 83 and 84 are in disc form and are mounted within and perpendicular to the axis of a circular wave guide 85. The coil 86 which is mounted on the wave guide 85 provides a longitudinal biasing magnetic field for the ferrite discs 81 through 84. The principles of Faraday effect rotation in polycrystalline ferrite materials are well known and are disclosed, for example, in C. L. Hogan's article entitled "The Microwave Gyration" which appeared at pages 1 through 31 of the January 1952 issue of volume 31 of the Bell System Technical Journal.

In addition to the basic nonreciprocal phase shifting devices shown in Figs. 7 through 10, the present single crystal ferrites may be employed in more complex microwave circuits. For example, they may be employed as nonreciprocal coupling elements in directional couplers, and they may be used to obtain the nonreciprocal effects required in microwave "circulator" structures.

In the devices of Figs. 7 through 10, the ferrite elements are cut from single crystals of ferrite material. The single crystals of ferrite may be formed by the flame fusion process, or may be obtained by crystallization from solution as explained in detail in J. Remeika application Serial No. 475,239, filed December 14, 1954, now United States Patent 2,848,310, issued August 19, 1958. The ferrites may have chemical formulae of the type MFe_2O_4 , where " M " represents one or more divalent metals. Typical ferrites which may be employed are $NiFe_2O_4$ or $(Ni_{0.7}Zn_{0.3})Fe_2O_4$. Other ferrites having even more than two divalent metals in the " M " position in the chemical formula set for the above may also be employed; however it is desirable that approximately stoichiometric proportions of the total amount of the divalent metals be maintained in their relationship with the Fe_2O_4 .

By way of illustration, the ferrite elements shown in Figs. 7 through 10 may be cut from single crystals of ferrite parallel to the 001 plane, and the biasing magnetic field is applied in the 001 direction perpendicular to the 001 plane. As explained hereinbefore, however, other crystal cuts and other orientations of the magnetic field are possible. Specifically the orientation of the biasing magnetic field in one of the principal coordinate planes of the crystal has been shown to produce the desired configuration of the surface representing the total magnetic energy of the ferrite element. From a physical standpoint, this results from the concavity of the anisotropy magnetic field characteristic shown in Fig. 1 along the principal coordinate planes of the crystal. To obtain the desired low frequency effects it is necessary that the surface representing the total magnetic energy characteristic be nearly flat. By applying a biasing magnetic field in a direction in which the anisotropy surface is convex with respect to at least one plane passing through the origin of the characteristic of Fig. 1, the combination of the two opposed fields may produce a relatively flat region. The application of a magnetic field to a concave point such as the 111 direction (the direction of easiest magnetization) of Fig. 1 can only increase the depth of the minimum, possibly reversing the direction of magnetization, and no flat region can be produced.

The distinction between the present ferrite elements cut from a single crystal and the polycrystalline ferrite elements of the prior art is again stressed. Up to the present time ferrite elements for microwave purposes have generally been formed either by sintering ferrite powders or by dispersing the ferrite powder in a dielectric material. The individual ferrite crystals in these polycrystalline ferrite elements are generally much smaller than one millimeter long and are oriented in a random manner. Because the low frequency nonreciprocal effects are strongly dependent on crystal orientation, they have

not been observed in the polycrystalline ferrite samples. Accordingly, the use of ferrite elements cut from a single crystal of ferrite and which are greater than one millimeter in their larger dimensions is considered to be an important factor in the successful operation of the present devices.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In an electromagnetic wave transmission system means including a waveguide for propagating an electromagnetic wave having a circularly polarized component of high frequency magnetic field, a single crystal of low conductivity ferrite of cubic symmetry having three mutually perpendicular crystal axes defining three principal coordinate planes, said crystal having a characteristic anisotropy field and a demagnetizing field, means for applying a magnetic biasing field to said crystal substantially in one of the three principal coordinate planes having a magnitude less than the sum of said anisotropy field and said demagnetizing field, and means for supporting said crystal in the field of said electromagnetic wave with said circular components of the high frequency magnetic field being perpendicular to said biasing magnetic field.

2. In an electromagnetic wave transmission system means including a waveguide for propagating an electromagnetic wave of a given frequency having a circularly polarized component of high frequency magnetic field, a single crystal of low conductivity ferrite of cubic symmetry having three mutually perpendicular axes defining three principal coordinate planes supported in the field of said electromagnetic wave, said crystal having a demagnetizing field and a characteristic anisotropy field

producing a natural resonance frequency greater than said given frequency, means for applying a magnetic biasing field to said crystal substantially in one of the three principal coordinate planes and perpendicular to said circular component of high frequency magnetic field, said biasing field having a magnitude less than the sum of said anisotropy field and said demagnetizing field to reduce the resonance frequency of said crystal from the frequency of said natural resonance to said given frequency.

References Cited in the file of this patent

UNITED STATES PATENTS

15	2,644,930	Luhrs	July 7, 1953
	2,649,574	Mason	Aug. 18, 1953
	2,817,813	Rowen et al.	Dec. 24, 1957

FOREIGN PATENTS

20	980,648	France	Dec. 27, 1950
----	---------	--------	---------------

OTHER REFERENCES

- Landau et al.: "On the Theory of the Dispersion of Magnetic Permeability in Ferromagnetic Bodies," *Physikalische Zeitschrift der Sowjetunion*, vol. 8, No. 2, 1955, pages 153-69.
- Belgers: "Measurements on Gyromagnetic Resonance of a Ferrite Using Cavity Resonators," *Physica*, XIV, No. 10, February 1949, pages 629-41.
- Holden: "Microwave Magnetic Resonance Absorption in a Nickel Salt near 1.25 cm., page 1443.
- Snoek: "Gyromagnetic Resonance in Ferrites," *Nature*, July 19, 1947, vol. 160, page 90.
- Bickford: *Physical Review*, vol. 78, May 1950, pages 449-457.
- Kip et al.: *Physical Review*, vol. 75 (1949), page 1556.