A Review of New Magnetic Phenomena

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As a result of new developments, the classical concepts of magnetic materials, characterized by hysteresis loss and eddy currents, are no longer adequate. Study of the ferrites has revealed new and important magnetic phenomena. These materials, because of their high resistivities and correspondingly low eddy currents, exhibit useful magnetic properties at frequencies well above those at which magnetic alloys are applicable. This paper reviews the new phenomena — domain wall motion and dimensional effects in the low megacycle region, and ferromagnetic resonance and the Faraday effect in the microwave region — and relates them to modern theory. Some possible microwave applications are discussed briefly.

I. INTRODUCTION

Up until a few years ago, the classical concept of magnetic materials, characterized by hysteresis and eddy current effects, was adequate for the communications engineer. Recent new and important developments, however, have made it necessary for him to have a broader knowledge of magnetic phenomena than is given by the old picture. Because of the low resistivities of existing magnetic materials, their properties at high frequencies have been dominated by eddy currents which in many cases have completely masked other magnetic effects. In contrast, the newly developed ferrites have resistivities from 10^6 to 10^{12} times greater, and eddy currents are usually negligible. The ferrites are, therefore, useful at far higher frequencies than previously available materials. Furthermore they have revealed new and important magnetic phenomena.

It is the purpose of this paper to present the modern picture of magnetism from the standpoint of the engineer. It describes the new phenomena and relates the experimentally observed behavior of magnetic materials at high frequency to the present physical theory of magnetism. The new phenomena include dimensional and domain wall motion effects in the low megacycle region and ferromagnetic resonance and the recently observed Faraday effect in the microwave region.

Although we are concerned more with magnetic phenomena than with the properties of particular materials, we will relate our discussion to ferrites, since these are the materials in which high frequency phenomena have been explored. We begin, therefore, with a brief description of these materials.

II. DESCRIPTION OF FERRITES

The term "ferrite" as used here refers to a class of ferromagnetic oxides that are structurally the same as magnetite (the naturally occurring magnetic mineral commonly known as lodestone) and as the mineral spinel from which the structure derives its name.[1, 2, 3] These compounds form extensive solid solutions of both the substitional and the subtractional type. Nickel zinc and manganese zinc ferrites are important examples of the substitutional type. In these, the zinc and nickel or manganese are thought to be in solid solution in magnetite (Fe_3O_4) where they have directly replaced equivalent amounts of iron in the lattice. An example of the subtractional type of solution is γ-Fe_2O_3. Here, oxygen is considered to be in solution in magnetite, not, however, having replaced iron, but having eliminated it, thus leaving vacant sites in the lattice. Magnetically, the ferrites are thought of as consisting of two interpenetrating lattices of metal ions whose magnetic moments point in opposite directions. Since, however, these moments are in general not equal, the material has a net magnetic moment.

Ferrites are manufactured by carefully mixing oxides of the constituent materials. The resulting powder is then pressed into desired shapes. These formed parts are fired at a temperature of 1000°C or more to produce the finished materials. The finished product is technically classed as a ceramic, and among its properties is extraordinarily high resistivity compared with magnetic alloys. Mechanically, ferrites have some of the characteristics of ceramics. They are extremely hard and brittle and cannot be machined by ordinary methods. They may be ground and lapped by use of abrasive cutting tools.

Experience has shown that the properties of the finished product depend upon composition (both what elements are present and in what proportions) and upon heat treating conditions (atmosphere, maximum firing temperature, and time of firing). It is apparent that, since there are so many possible variables in manufacturing procedure, one may expect a wide variety of electrical and magnetic characteristics.

Ferrites have been commercially available for several years. NiZn ferrite is being used extensively in deflection coils and flyback transformers in television sets. MnZn ferrite has found specialized but important use in inductors for networks and in transformers in telephone circuits. Magnetic recording tape makes use of γ-Fe_2O_3. An increasing amount of information of interest to the design engineer is becoming available in manufacturers' catalogs.

III. DC CHARACTERISTICS

For convenience in the following discussion, the frequency range under consideration has been divided somewhat arbitrarily according to the magnetic phenomena which have been observed. We will begin by discussing dc behavior of magnetic materials.

As far dc magnetic properties are concerned, the modern picture is the same as the classical one. The study of ferrites has revealed no essentially new phenomena, at least so far.

Hysteresis loops for typical ferrites are shown in Fig. 1, together with loops for iron and for permalloy. It will be observed that some ferrites compare favorably with permalloy with regard to hysteresis loss (proportional to the area of the hysteresis loop). Their saturation flux density is considerably lower, the maximum so far obtained being between 4,000 and 5,000.

By applying pressure to a sample and thereby introducing strain, some investigators have found it possible to produce ferrite cores having practically rectangular hysteresis loops,[4] just as similar effects have previously been obtained with permalloy and other magnetic material.

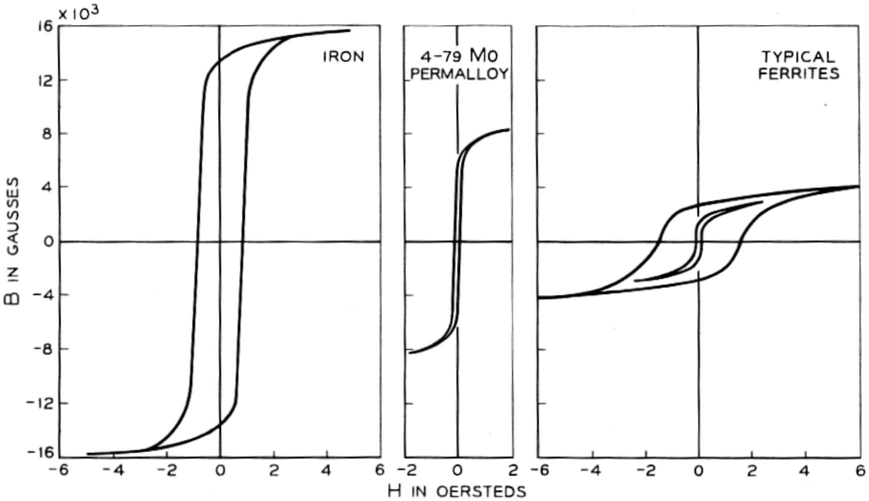


Fig. 1 — Hysteresis loops of iron, permalloy and typical ferrites. The thin ferrite loop is for a MnZn ferrite, while the larger loop represents a NiZn ferrite.

Such cores find an important application in memory circuits employed in connection with digital computers. Suitably cut ferrite single crystals also exhibit rectangular loops when properly annealed.[5]

Initial permeability of ferrites has a wide range of values depending upon the material under consideration. It may be as low as 4 for magnetite and as high as 3,000 for manganese-zinc ferrites. Curie temperature (the temperature above which the material no longer exhibits ferromagnetic properties) is around 80°C for the high permeability MnZn materials and is several hundred degrees C for the low permeability nickel ferrite. Resistivity also depends upon the composition of the material. Typical data gives values of 100 ohm-cm for a MnZn ferrite and 10^6 ohm-cm for a NiZn ferrite. The commonly used metallic magnetic materials have resistivities of the order of 10^{-5} ohm-cm. As mentioned above, this much higher resistivity is the feature of ferrites which makes possible their application at frequencies where ordinary metallic materials are generally not usable. At dc the dielectric constant of ferrites is high. Determination of dielectric constant is rather difficult, but the best measurements to date indicate values of from 10 to 30.

IV. LOW FREQUENCY PHENOMENA (0 to 1 mc)

A convenient and commonly used method of determining low frequency characteristics of magnetic materials consists in making bridge measurements of inductance (L) and effective series resistance (R) of a uniform winding placed on a toroidal core of the material. Subtraction of the dc winding resistance gives a value of resistance (R_m) which represents the core loss in the material. Permeability may be calculated from the inductance measurements. The method of analysis described by Legg[6] may be applied to powdered or laminated alloys. The method consists essentially in determining the coefficients in the equation

$$R_m = e\mu f^2 L + a\mu B_m f L + c\mu f L, \tag{1}$$

where B_m is maximum flux density, μ is permeability, f is frequency, and e, a and c are constants. For alloys in laminated or powder form these constants are associated respectively with eddy current, hysteresis, and residual losses. From measurements of L and R_m at two or more frequencies with a fixed flux density, B_m, and two or more values of flux density at a fixed frequency, f, the coefficients e, a and c can be determined by solving the simultaneous equations obtained from equation (1).

Equation (1) is equally applicable to the ferrites at frequencies below that at which domain wall resonance and dimensional effects (discussed in Sections VI and VII) begin to appear. This frequency, which is somewhat below that indicated by f_1 in Fig. 3, depends upon the particular ferrite. The range of applicability of equation (1), therefore, varies. Regardless of frequency, the eddy current and hysteresis terms in equation (1) are valid. However, additional terms are required to cover other losses which become quite high and in comparison with which the "residual" term in equation 1 may be negligible.

Frequently, the separation of losses indicated in equation (1) is not called for. The practice then is to lump all losses together and express them in terms of the material Q, which may be a function of frequency and flux density. Here Q is the ratio of the reactance of the winding on a toroidal ring to the core loss expressed as a series resistance,

$$Q = \frac{\omega L}{R_m}.$$

The product μQ is convenient in describing magnetic characteristics. Sometimes air gaps are introduced in ferrite magnetic cores in order to provide higher coil Q's or greater stability of *ac* permeability with superposed *dc* magnetizing force. It can be shown that the product μQ remains constant even though the core is divided by one or more air gaps. Fig. 2 shows curves of μQ versus frequency for various ferrites and also for certain other materials. An extensive discussion of methods of measurement and of results of measurements at low frequencies is given in a recent paper by Owens.[7]

It should be pointed out that eddy currents in ferrites are so small that solid shapes are usually used whenever ferrites are applicable. This is a considerable advantage, eliminating the necessity for thin tapes or insulated fine particles which are required in many applications of metallic cores. However, so far, no ferrite has been developed which has permeability nearly as great as that of some of the permalloys.

V. CHARACTERISTICS ABOVE 1 MC

So far, our discussion has covered the frequency range in which magnetic materials have traditionally found many important uses and in which the ferrites have properties generally like other magnetic materials, differing from them only in degree. We now come to the frequency range in which new magnetic phenomena have recently been observed — a range above that in which magnetic materials have heretofore been generally applicable.

In discussing the higher frequency characteristics, it is desirable to introduce a somewhat different set of parameters by which the properties

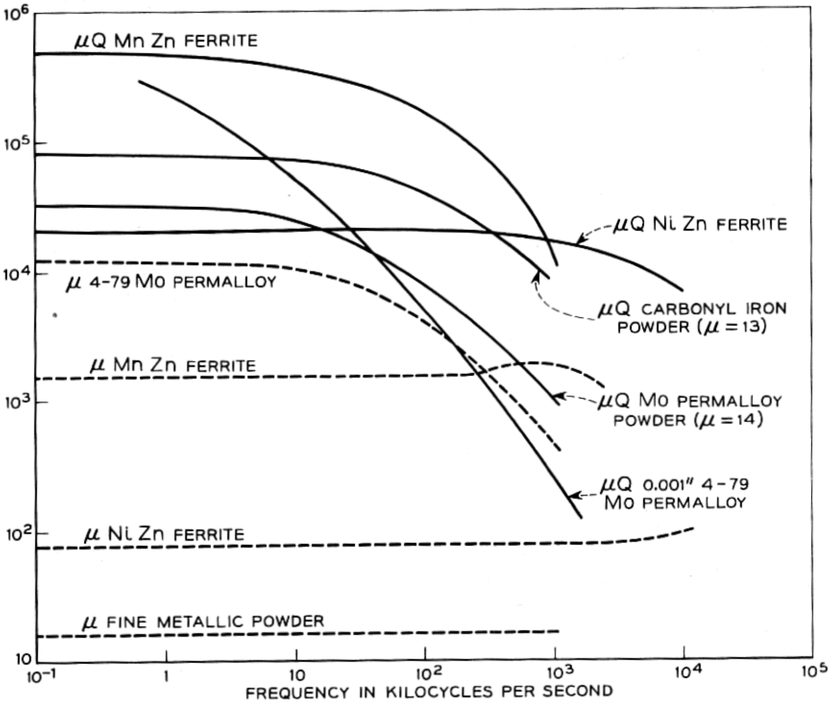


Fig. 2 — Comparison of the frequency variation of μ and μQ for ferrites and other magnetic materials.

may be described. This comes about because the ferrites, in which the new effects are observed, have both dielectric and magnetic properties. The material is most conveniently described in terms of two complex quantities: the permeability, $\mu = \mu' - j\mu''$, and the dielectric constant, $\epsilon = \epsilon' - j\epsilon''$. μ' corresponds to the usual low frequency permeability and $Q = \mu'/\mu''$. Similarly ϵ' corresponds to the usual low frequency dielectric constant, while $\epsilon''/\epsilon' = \tan \delta$, the loss tangent of the material. Thus the quantities μ'' and ϵ'' are measures of the magnetic and dielectric losses per cycle respectively, in the material.[8] The fact that μ'' and ϵ'' represent loss *per cycle* means that much higher values of these quantities can be tolerated at low frequency than at microwave frequencies.

At frequencies above a few megacycles, it becomes very difficult to make meaningful observations on wound toroidal cores. Such difficulty may be overcome by making measurements on a toroidal sample placed in a coaxial line. Details of the experimental procedure may be found in references 9 through 12. The same procedure may be applied at microwave frequencies with waveguide used instead of coaxial line. In this case, the sample is in the form of a slab, cut to fit snugly against the walls of the waveguide.

Fig. 3 shows in a qualitative way the behavior of a typical ferrite. In this figure we have plotted the real and imaginary parts of permeability as functions of frequency. Examination of the results obtained by various investigators for a number of different ferrites leads to the conclusion that they all behave in a fashion similar to that shown in Fig. 3. Frequency f_1 usually lies in the region between 1 and 100 mc and f_2 frequently lies in the neighborhood of 3000–4000 mc. Available data are not sufficient to provide similar curves for dielectric constant, but what there are indicate a decrease from the very high apparent value at low frequencies to a constant value of the order of 10. This decrease generally occurs somewhere around 10 mc, although it depends upon the material and also probably upon sample dimensions as will be discussed below.

The consensus is that the high experimental values of dielectric constant observed at low frequencies result from the peculiar structure of ferrites. They are considered to consist of grains of conduction material (of moderately high conductivity) separated by thin layers of dielectric material having a dielectric constant of the order of 20. Measurements on such a structure would give very high apparent dielectric constant and low Q. Such behavior was observed several years ago in samples of powdered permalloy, and has also been found in samples of plastic in which finely divided particles of copper have been dispersed.

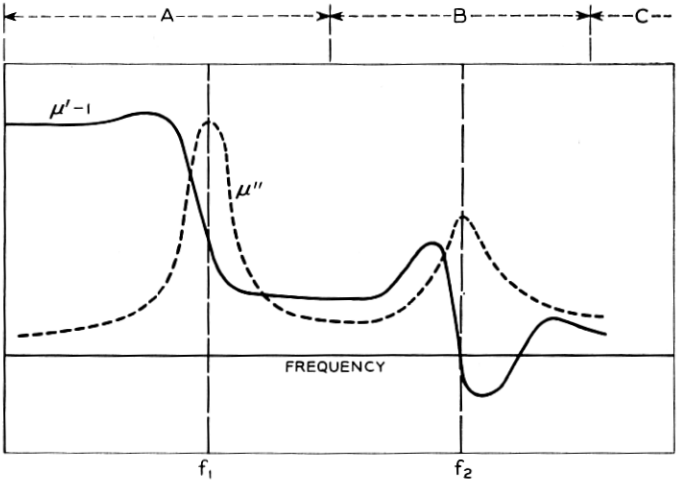


Fig. 3 — Frequency characteristics of a typical ferrite. The components of complex permeability ($\mu = \mu' - j\mu''$) as functions of frequency. The behavior in the neighborhood of f_1 is attributed to domain wall motion or to dimensional effects. f_2 represents the frequency at which ferromagnetic resonance occurs.

For convenience in the following discussion, Fig. 3 has been divided into three regions as indicated. It will be observed that there are two peaks in the curve of μ'' versus frequency, one in Region A and the other in Region B. The frequencies at which these occur are those at which relatively large amounts of energy are absorbed by the material. These two absorption peaks are due to entirely different mechanisms within the ferrite and it is, therefore, of interest to consider them separately. We begin with Region A.

The behavior indicated in Region A is typical of polycrystalline samples of ferrite (as distinguished from single crystals which will not be considered here). μ' rises somewhat above its constant low frequency value and then decreases rather suddenly. If f_1 denotes the frequency at which the peak in μ'' occurs, we find that in general a high value of μ' at low frequency is associated with a low value of f_1, and vice versa.

At the present time, we are not sure which of two experimentally observed effects in the ferrite is responsible for the behavior shown in Region A. It is quite likely that what one observes in a given sample is actually a combination of the two effects, domain wall motion and dimensional resonance, each of which will now be described.

VI. DOMAIN WALL MOTION

The basic unit of magnetism is the spinning electron. In an atom of ferromagnetic material, there is an excess of electrons with spins in one particular direction. As a result, the atom has a net magnetic moment. Any ordinary sample of ferromagnetic material consists of many small, irregular volumes called domains, each of which may contain many atoms. Each domain is completely magnetized along some direction. Both the size of the domains and the directions of their magnetizations vary from point to point throughout a sample. In an unmagnetized material, the random orientation of individual domain magnetizations results in a mutual cancellation of their effects. However, if a magnetic field is applied, certain domains will be in a preferred orientation, having their magnetic moments more nearly in the direction of the applied field than others. These will grow at the expense of less favorably oriented domains by a process of motion of the walls separating adjacent domains. When an alternating field is applied, the walls will be subject to an alternating force which will tend to move them first in one direction and then in the opposite direction. Now it has been shown[13] that, under these conditions, the permeability of the material is proportional to the ease of displacement of the domain walls. Therefore, if we can predict how a wall will move as the frequency of the applied field changes, we can predict how the permeability will change with frequency.

The walls have been found to exhibit properties of mass and stiffness and to be subject to damping. Thus it is possible to write an equation which describes the motion of a wall under the influence of an alternating field.[13, 14] If x is the displacement of the wall from its equilibrium position, then

$$m \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + \alpha x = M_s He^{j\omega t}, \tag{2}$$

where m = mass/unit length of wall,

β = damping coefficient,

α = stiffness parameter,

M_s = saturation moment of sample,

$He^{j\omega t}$ = applied field,

This equation should look familiar to electrical engineers. It has the same form as that for an RLC circuit subject to a sinusoidal applied voltage.[15] If the damping constant is not too great, we would expect the wall motion to have a resonance at a frequency, f_0, for which

$$\omega = \sqrt{\alpha/m}.$$

Fig. 4 shows the expected variations of μ' and μ'' in the vicinity of resonance under these conditions.

If, however, the mass of the wall is negligible, the situation is somewhat different. In this case, μ'' has a maximum at a frequency for which $\omega = \alpha/\beta$, while μ' decreased monotonically from its low frequency value, reaching ½ this value at $\omega = \alpha/\beta$. It is apparent that this behavior is analogous to that of an RC circuit. It is commonly known by the term "relaxation". We see, therefore, that, depending upon wall mass, there are two possible ways in which wall motion may contribute to the behavior shown in Region A of Figure 3, namely, through domain wall resonance and through domain wall relaxation.

VII. DIMENSIONAL RESONANCE

The second phenomenon which may aid in accounting for the behavior indicated in Region A is dimensional resonance. In 1950, Brockman, Dowling, and Steneck[16] reported the results of some experiments on a manganese-zinc ferrite known commercially as Ferroxcube III. Using blocks of this material, they built a closed rectangular core. Measurements on a winding placed on this core showed behavior like that of region A with f_1 lying between 1 and 2 mc. When they decreased the

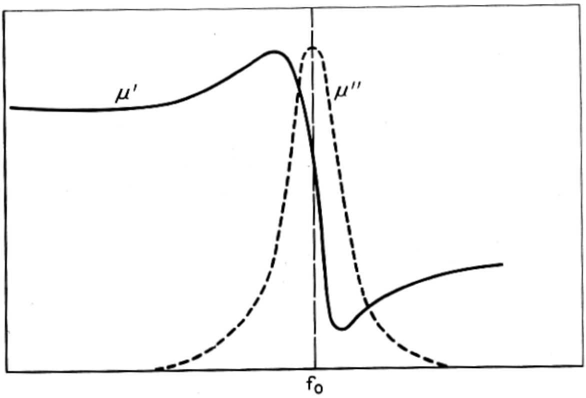


Fig. 4 — Typical behavior of the components of complex permeability ($\mu = \mu' - j\mu''$) in a ferrite in the neighborhood of domain wall resonance.

cross section area, f_1 moved to a higher value. Brockman, Dowling and Steneck attributed this to a cavity type resonance effect resulting from a high dielectric constant which gave wavelengths in the material of the same order of magnitude as the dimensions of the sample under test. Another way[17] of looking at the phenomenon is to recognize that in the ferrites there are displacement eddy currents which correspond to the conduction eddy currents in magnetic alloys. Analysis based on this approach gives resonance frequencies which are the same as those calculated by Brockman, Dowling and Steneck.

In any sample it is possible that both mechanisms — domain wall motion and dimensional resonance — contribute to the behavior of the material in Region A. Futhermore, it is evident that considerable caution is required in interpreting results of experiments designed to measure μ and ϵ as functions of frequency. One must always bear in mind that what one obtains is the *effective* μ and ϵ of the sample under test, and the actual μ and ϵ for the material may be different from the observed values, depending upon the effect of sample dimensions.

It is clear that in a design problem the communications engineer must take into account the dimensions of the ferrite part as related to the permeability and dielectric constant of the material and to the frequency at which it is being used. This may impose a practical limitation on the size of a part for a particular application.

VIII. FERROMAGNETIC RESONANCE

The behavior indicated in Region B of Fig. 3 is attributed to ferromagnetic resonance. This phenomenon was first observed in magnetic metals by Griffiths[18] and has been studied intensively in ferrites.[21]

Consider a single electron. Because it is a spinning charge, it has a magnetic moment which lies along its axis of spin. Because it has mass, it has mechanical angular momentum. The ratio of these two quantities is the magnetomechanical ratio, γ. If a steady magnetic field, H_0, is applied, there will be a torque on the electron as a result of the interaction between H_0 and the magnetic moment of the electron. The electron will, therefore, precess about the direction of H_0 with a frequency which has been shown to be given by $\omega_0 = \gamma H_0$. This phenomenon is the well-known Larmor precession.[19] We may say then, that the electron has a resonance frequency ω_0.

Now suppose a sample of ferrite to be placed in a magnetic field H_0. By virtue of the contributions of its many spinning electrons, the sample has a magnetic moment, M. If H_0 is a strong field, M will be parallel to H_0. However, there will be, as in the case of the single electron, a frequency at which M will precess about the direction of H_0. This precession frequency is proportional to an effective field, H_e, and to M/J, where J is the vector sum of the individual angular momenta of the electrons. H_e is a function of H_0 and also of the demagnetizing fields within the ferrite. If an alternating field of this frequency is supplied perpendicular to H_0, then absorption will occur. The amplitude of the precessional motion will become such that the energy supplied by the alternating field is equal to the energy transformed into heat in the sample. At the resonant frequency, μ' is equal to 1 and μ'' reaches a maximum.

Although the above discussion postulates a strong external field, a more detailed analysis leads to the conclusion that resonance may be expected even with zero external field. This is attributed to the presence of internal fields which result from such things as crystal anisotropy, magnetostrictive strain, and internal demagnetizing fields in the material. These demagnetizing fields are generally the most important factor in determining the resonant frequency of a demagnetized ferrite.

A number of investigators have studied ferromagnetic resonance in ferrites. Some experimental methods and results are described in References 19 through 23. Much of the investigation has been carried out on single crystals of ferrite. In these cases, the experimental results depend upon the orientation of the crystal axis with respect to the external field. In the case of polycrystalline samples, the resonance is still present, but the resonance is not as sharp.

Most of the experiments in which ferromagnetic resonance has been studied have been with fixed frequency and varying magnetic field. Fig. 5 shows some typical results of such an experiment. From a practical experimental standpoint, this is preferable to varying frequency with a fixed magnetic field. However, it is apparent that if one holds the magnetic

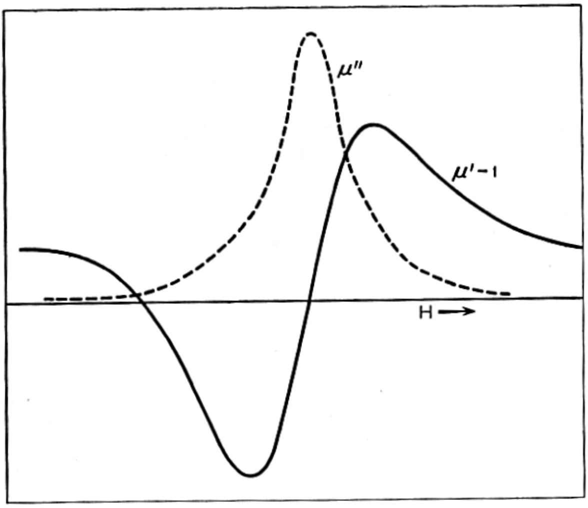


Fig. 5 — Behavior of a magnetic material in the neighborhood of ferromagnetic resonance. This represents the usual experimental situation, where frequency is kept constant and the external magnetic field is variable.

field constant at some value H_0 and varies the frequency, one will obtain curves similar to those of Fig. 5. This is indicated in Region B of Fig. 3. Furthermore, for a given sample, as H_0 increases, the frequency at which resonance occurs increases.

IX. MICROWAVE FARADAY EFFECT

If a linearly polarized wave of microwave frequency travels through a ferrite which is magnetized in the direction of propagation of the wave, the plane of polarization will be rotated. The sense of the rotation depends only upon the direction of magnetization of the ferrite and is independent of the direction of propagation of the wave. Thus the effect is anti-reciprocal.

This phenomenon, which derives its name from the analogous optical effect was demonstrated experimentally by Roberts[24] and has been extensively investigated by Hogan.[25] It occurs at frequencies above the ferromagnetic resonance frequency, that is, in Region C of Fig. 3. In principle, the effect might be expected in any ferromagnetic material but, so far, only the ferrites are sufficiently transparent to microwaves to allow the effect to be detected. The effect is illustrated in Fig. 6. The linearly polarized microwave in waveguide A passes through a transition section into the circular guide B. A tapered cylinder of ferrite is inserted in B. A solenoid, external to B, supplies a steady field parallel to the axis of propagation. Upon emerging from the sample, the wave passes into C, a circular to rectangular waveguide transition which may be rotated for maximum transmission of energy down section C. The angle of displacement of C with respect to A is a measure of the rotation of the plane of polarization of the wave in its passage through the ferrite. The rotation per centimeter of material depends upon the longitudinal field in the sample, increasing with this field and reaching a constant value when the ferrite is saturated.

Hogan[25] has given a discussion of the theory of this ferromagnetic effect. The incident linearly polarized wave may be described as a combination of two oppositely rotating circularly polarized waves. The real part, μ', of the permeability of the ferrite varies with magnetic field in a different way for the two circular polarizations, as shown in Fig. 7. The velocity of propagation of the two polarizations is therefore different, and in passing through the ferrite they will fall out of phase by an amount proportional to sample length. Upon emerging they will combine to form a linearly polarized wave whose plane is rotated with respect to the incident wave. Reference to Fig. 7 shows that the most useful region for obtaining this effect lies below the field required to produce ferromagnetic resonance (i.e., at frequencies above the ferromagnetic resonance frequency) in the region where the two curves are practically parallel. In this region the device is relatively insensitive to small field changes and is somewhat "broadband" with respect to frequency.

For the practical application of the Faraday rotation, it is desirable that the attenuation per degree of rotation be small. Attenuation varies widely for different kinds of ferrites and is a function of frequency. For

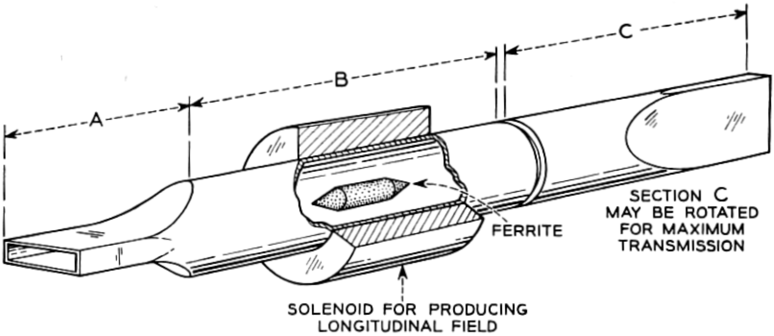


Fig. 6 — Apparatus for demonstrating the microwave Faraday effect. Energy is supplied to section A. Rotation of plane of polarization occurs in section B and is controlled by controlling the longitudinal field. Section C is rotated for maximum transmission. The angular displacement of C with respect to A is a measure of the rotation.

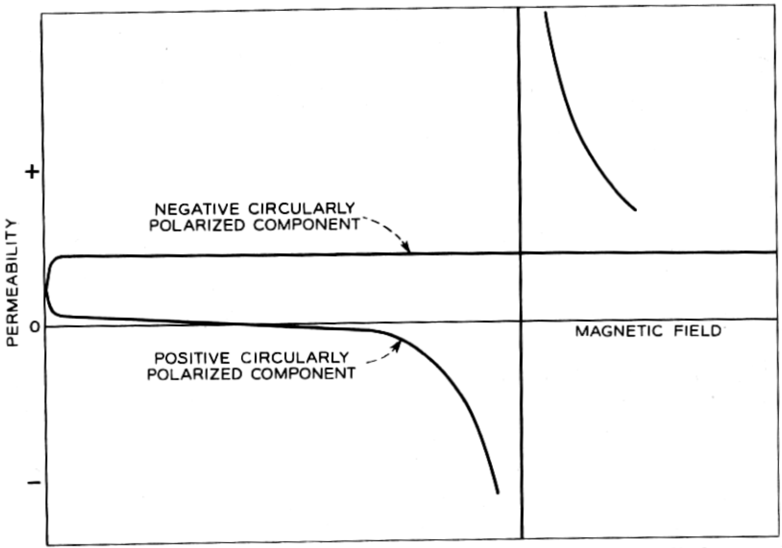


Fig. 7 — Real part (μ') of permeability of a ferrite versus applied magnetic field for the two circularly polarized components into which an incident plane wave may be resolved. The useful region for the Faraday effect is that for low H, where the two curves are approximately parallel.

one sample at 9,000 mc, Hogan found a rotation of 60 degrees per cm of path and an attenuation of about 0.5 db per cm.

X. EFFECT OF CROSS FIELD

When a steady magnetic field is applied to a ferrite in a direction perpendicular to the path of transmission of electromagnetic waves through the material, the effective ac permeability of the material varies with the applied magnetic field. For a given frequency, the permeability starts out positive. As the magnetic field increases the permeability goes through zero and approaches a large negative value as ferromagnetic resonance is reached. Above resonance the permeability is positive and gradually decreases with increase in magnetic field.

Since the characteristic impedance of the ferrite relative to an empty waveguide is

$$Z = \sqrt{\frac{\mu}{\epsilon}},$$

it is apparent that Z may be varied by changing the applied field. When μ is zero, the ferrite appears to be a perfect reflector, while when $\mu = \epsilon$, it provides a perfect match to the empty guide. Since it is possible to vary the characteristic impedance over a wide range, this effect has possibilities of application in attenuators, modulators, and phase shifting devices.

XI. NEW MAGNETIC APPLICATIONS

The engineer is naturally interested in some of the uses to which the new magnetic phenomena may be put. Several applications will be described briefly.

1. The gyrator. This is a four pole element for which there is a 180° phase difference between the two directions of propagation. In other words, the transfer impedances in the two directions are equal in magnitude but opposite in sign. Thus the device violates the reciprocity theorem.

Hogan[25] built the first microwave gyrator using the arrangement shown in Fig. 8. In this device, a wave traveling from left to right has its polarization rotated 90° counter-clockwise in the twisted section and another 90° in the same direction by the ferrite — a total rotation of 180°. For a wave traveling from right to left the two rotations, that in the ferrite and that in the twisted section, cancel each other. Thus, if A and B represent points of the same phase for a left-to-right wave, they represent points of 180° phase difference for a right-to-left wave.

2. One way transmission system. If the input and ouput waveguides in Fig. 6 are oriented with their planes at 45° to each other and if the solenoid current is adjusted for 45° rotation in the ferrite, the result is a one-way transmission system.[25] Such a device is broadband. An arrangement of this sort may be employed in a microwave system to isolate the transmitter or receiver from the waveguide. It has the advantage that loss in the forward direction can be made quite small by proper choice of material.

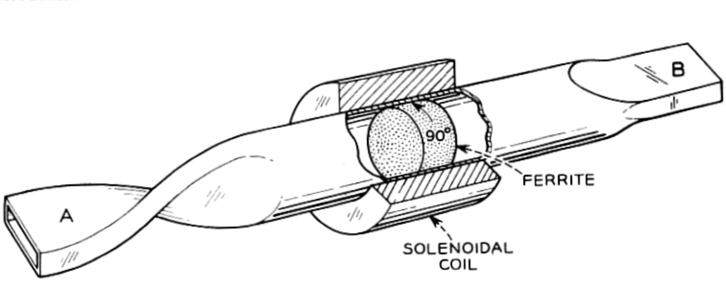
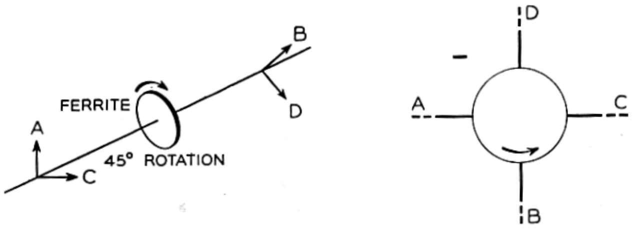


Fig. 8 — Schematic diagram of a microwave gyrator. From left to right, the plane of polarization is rotated 180°; corresponding to a phase shift of π. From right to left, the plane of polarization is not rotated and the phase shift is therefore zero.

3. The polarization circulator. This is a modification of the one way transmission system in which there are two connections, with polarizations at 90° to each other, on either side of the ferrite rotating element. This is shown schematically in Fig. 9, along with a symbol which has been suggested for this element.[25] Energy sent into the device with polarization A emerges with polarization B, polarization B is rotated into C polarization C is rotated into D, and polarization D emerges as *minus* A. One practical application of this device is as a TR box in a radar system. Another, recently suggested by A. G. Fox, is as a device for separating the various channels in a multichannel communication system. Referring to Fig. 10, the signal comes in at A. Branch B is terminated in a filter which accepts one channel but reflects the remainder of the signal which is passed on to C. Here another filter accepts the second channel but passes the remainder on to D. D in turn feeds a second circulator. This process can go on until all channels are taken care of.

4. Measurement of magnetic field strength. The phenomenon of ferromagnetic resonance suggests a means of making measurement of magnetic field strength by observing the resonance frequency for a ferrite when subjected to the unknown field.[26] Allen[27] has recently described a magnetometer in which an unknown field is measured by observing the Faraday rotation which it produces in a standard sample.

5. Other applications. There are several ways in which the interaction of the steady field with the microwave field may be utilized in designing switches, attenuators, and modulators. For example, one might set the two rectangular guides in Fig. 8 with their transmission planes at 90°. Then by varying the current in the solenoid and thereby varying the magnetic field applied to the ferrite, one may vary the amount of energy accepted by the second waveguide. This is then an electrically controlled attenuator. This same device offers the possibility of providing modulation of the microwave signal by modulating the current in the solenoid.



POLARIZATION CIRCULATOR

CIRCUIT SYMBOL

Fig. 9 — Schematic representation of polarization circulator. The ferrite is adjusted to 45° rotation by an external field, not shown. The circuit symbol for the circulator is shown at the right.

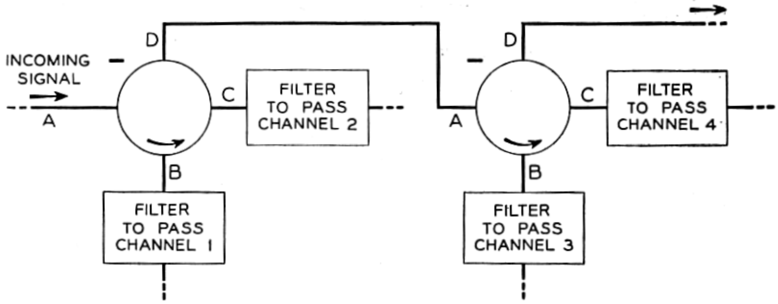


Fig. 10 — Schematic diagram showing the proposed use of circulators to separate the various channels in a multichannel communication system.

Reggia and Beatty[28] have recently described a coaxial line variable attenuator in which the transmission loss is controlled by variation in an external cross field.

XII. CONCLUSION

From the discussion which has gone before, it should be apparent to the communications engineer that a whole new field of applications of magnetic materials has opened up. It is therefore essential that the engineer be acquainted with the modern picture of magnetism including the phenomena which have been described here — low frequency resonance, ferromagnetic resonance, and microwave Faraday effect. Some applications have already been made of the high frequency characteristics, particularly of the Faraday rotation. Knowledge of the general high frequency characteristics of magnetic materials will enable the engineer to interpret new experimental information as it becomes available and intelligently to utilize the new materials in a variety of engineering applications.

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