PROPERTIES OF FERRITES IN WAVEGUIDES*

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In the past few years research with ferrites has shown that these materials possess unusual properties of considerable importance to microwave engineers. These properties result from the fact that at microwave frequencies and in the presence of a static magnetizing field, these non-conducting ferromagnetic media are characterized by an asymmetric tensor permeability whose components are functions of the static magnetizing field. Because of this one can, by means of a variable magneto-static field, vary the propagation characteristics, e. g., the phase, polarization, and transmission loss of a wave propagating in waveguide-containing ferrite materials. Since the static magnetizing field can be varied by purely electrical means, it is possible with the use of these materials to construct microwave components which will very rapidly vary either phase of polarization electrically.

At the Naval Research Laboratory, we have been engaged in a study of the propagation characteristics of the ferrites at X-Band and we would like to discuss a few of the results of that study.

Although it would be desirable to make measurements of the intrinsic properties of the ferrite materials with a view to ultimately being able to predict propagation characteristics in waveguides containing ferrites, such an approach entails many difficulties. Instead, we have chosen to measure the propagation characteristics directly, using ferrite-loaded waveguides. In this manner we measure the effects of the ferrite materials under conditions similar to those under which they will be used.

Clearly, the results of such measurements will depend not only on the intrinsic properties of the ferrites but also on the dimensions of the waveguide, the dielectric constant of the other media present in the waveguide, and the shape of the ferrite. Therefore, it should be kept in mind that the data which will be presented apply only to the geometry described, and may not, in general, be used to predict behaviour in other configurations.

In spite of these reservations, it is our hope that the results of our studies can be useful in understanding some of the intrinsic properties of the ferrite materials.

We would like to point out that the data to be presented were chosen as being typical of the behaviour of the ferrites we have examined and do not represent the best results which have been obtained as far as practical applications are concerned.

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One of the properties with which we have been concerned is the Faraday effect in waveguide, that is, the rotation of the plane of polarization of a plane wave when it propagates through a section of circular waveguide containing a cylinder of ferrite magnetized along the direction of propagation. We are interested in obtaining a large amount of rotation per unit length of the ferrite, while at the same time maintaining the power absorption per unit length as small as possible.

Fig. 1 shows a curve of the Faraday rotation obtained with a cylindrical piece of Ferramic A-34, a magnesium-manganese ferrite, 1/4 inch in diameter and 1-1/2 inch in length, located axially in a circular waveguide and supported by means of a polyfoam cylinder. The operating frequency is 9375 mc. An axial magnetic field is applied by means of a solenoid wound about the waveguide.

This curve is typical of most ferrites we have examined, the angle of rotation of the plane of polarization increasing linearly and then leveling off to the saturation rotation when the material becomes saturated. As can be seen, the power absorbed by the ferrite is a function of the magnetizing field.

If one uses the ferrite to produce a fixed rotation, it is clear that it is very desirable to choose the dimension of the ferrite so that it produces the desired rotation when it is saturated, since in that condition the rotation is insensitive to variations in the magnetizing field. Accordingly, the data presented are restricted to ferrite polarization rotators operating in the saturation region. If the diameter of the ferrite cylinder is kept constant and the length increased, and if end effects could be neglected, it would be expected that the amount of rotation absorbed power would increase linearly with length. We have checked the dependence on length experimentally and, except for some end effects in the longer diameters, both the saturation loss in db and the saturation rotation vary directly as the length. Therefore the ratio of saturation loss to saturation rotation is independent of length.

Fig. 2 shows the saturation rotation per unit length as a function of sample diameter for samples of the same A-34 material. The rotation increases slowly with diameter until one reaches a diameter of about 1/8 inch and then increases more rapidly until a diameter of about 1/4 inch is reached. Beyond this, large fluctuations occur in the rotation and absorption curves. The diameter at which these fluctuations set in depends on the particular ferrite.

A significant factor in the design of a rotator is the absorption loss per degree of rotation. The dependence of this ratio upon diameter is also shown in Fig. 2. Note that the loss per degree of rotation decreases as the sample diameter is increased. Therefore, if one were to build, for example, a 45 degree rotator polarization rotator using a length of ferrite 1/8 inch in diameter, the absorption loss would be 1 db. If, however, the same 45 degree rotator utilized a cylinder 1/4 inch in diameter, the absorption loss would be reduced to 1/4 db.

The variation of the saturation rotation with frequency is shown in the next figure. In Fig. 3 can be seen the deviation of saturation rotation from the value it has at 9375 mc for three samples of different diameters and same length. The rotation increases with frequency for all three samples, the rate of increase being greater as the diameter increases. From these curves we see that for a fixed amount of rotation, the bandwidth of the rotator increases as the diameter of the sample is decreased. Therefore, as one increases the diameter of the sample to obtain less power absorption, he must pay for it by having a smaller bandwidth.

Another aspect of our work is concerned with a study of propagation in a ferrite-loaded rectangular waveguide. While for the rotation measurements we applied an axial magnetizing field, in this case we apply a magnetizing field transverse to the axis of the waveguide. The propagation characteristics, e. g., the phase velocity and the power absorption, depend of course upon the shape and placement of the sample in the waveguide.

The general geometry involved can be seen in Fig. 4. The magnetizing field is applied in a direction perpendicular to the broad face of the guide along the x-axis and the direction of propagation is along the y-axis.

One of the interesting features of this situation is that the ferrite and the magnetizing field can be so disposed as to obtain propagation characteristics which are either reciprocal or non-reciprocal. For example, it can be shown that for the arrangement shown in this figure, where the ferrite section is situated asymmetrically with respect to the central plane, the propagation characteristic will be non-reciprocal. On the other hand, if the ferrite is symmetrically placed, the propagation will be reciprocal.

Fig. 5 shows the absorption losses and phase shift for a symmetrical placement of the ferrite in the waveguide. As can be seen, the phase shift and loss is the same for the two directions of propagation. This arrangement is useful for a reciprocal variable phase-shifter. With this particular sample, a magnesium-manganese ferrite, we can obtain any phase shift between 0 and 80 degrees with an absorption loss of less than 1 db.

Fig. 6 shows the non-reciprocal behavior we get if we place the ferrite against the side wall. Here we have a phase velocity which is different for the two directions of propagation. For this case, it happens that the losses are about the same for the two directions of propagation for the values of the magnetizing field shown. This arrangement might be used for a non-reciprocal phase shifting device. With the sample shown one can obtain a 65 degree difference in phase shift between the two directions of propagation with an absorption loss of less than 1/2 db. By choosing the proper length, one can obtain any desired differential phase shift, 180 degrees, for example.

A particularly interesting application of the non-reciprocal characteristics of the asymmetrical configuration is the construction of a one-way transmission line which absorbs most of the power for one direction of propagation, but transmits most of the power in the other. An understanding of how this can be done can be obtained from the theory of gyromagnetic resonance. If the rf magnetic field is circularly polarized in a plane perpendicular to the magnetization of the ferrite, a large resonance absorption of power from the rf wave should occur at that value of the magnetizing field which brings the ferrite into gyromagnetic resonance, whenever the sense of the circular polarization is positive with respect to the magnetizing field. Such resonance absorption should not occur for the negative sense of circular polarization.

For a waveguide-propagating energy in the dominant TE_{10} mode, there are two parallel planes such that the H-vector is circularly polarized in one sense in one of these planes, and in the opposite sense in the other. This can easily be seen from Fig. 7. It will be recalled that the longitudinal and transverse components of H are in phase quadrature. The variation in amplitude across the guide of the two components is shown in the diagram. At two planes, equi-spaced about the center line, the amplitudes are equal, so that the total H-field is circularly polarized. The longitudinal component, however, has the reverse sign at one plane with respect to the other. Since the change in sign is equivalent to a 180 degree difference in phase of the longitudinal component at the two planes, the sense of circular polarization is positive at one plane and negative at the other.

If the direction of propagation is reversed, the sign of the longitudinal component changes at both planes, and the sense of polarization reverses at both planes. Therefore, one would expect that if a piece of ferrite were placed along the plane where the rf H-field is circularly polarized in the positive sense with respect to the applied magnetizing field, there would be a large resonance absorption of power at that value of magnetizing field which brings the ferrite into gyromagnetic resonance. If the magnetizing field is now kept at the value necessary for resonance and we reverse the direction of propagation, the rf magnetic field incident on the ferrite will be circularly polarized in the negative sense with respect to the magnetizing field, and therefore there will be no resonance absorption. Since the resonance process usually is accompanied by absorption losses of at least 20 db, we have here a one-way transmission device.

Fig. 8 shows some experimental verification. The curve represents absorption loss versus magnetizing field for each direction of propagation. For the wave propagating in the +y direction, the loss is very small until the magnetizing field approaches the resonance value. In the resonance region the absorption loss becomes very high, the transmitted power being down 26 db. The wave traveling in the -y direction suffers very small losses until it reaches the field required for resonance, where the absorption rises to 2 db. If we therefore maintain a constant current of 21 amperes through our magnet we have a one-way transmission line with a differential transmission of about 24 db.

Fig. 9 shows the variation of relative phase in the same arrangement. Again we can see the non-reciprocal nature of the configuration. The wave traveling in the +y direction suffers an increase in phase while the wave traveling in the opposite direction has its phase velocity decreased. It is interesting to note the typical change in sign of phase generally associated with resonance for the wave which undergoes the resonance absorption.

Acknowledgment

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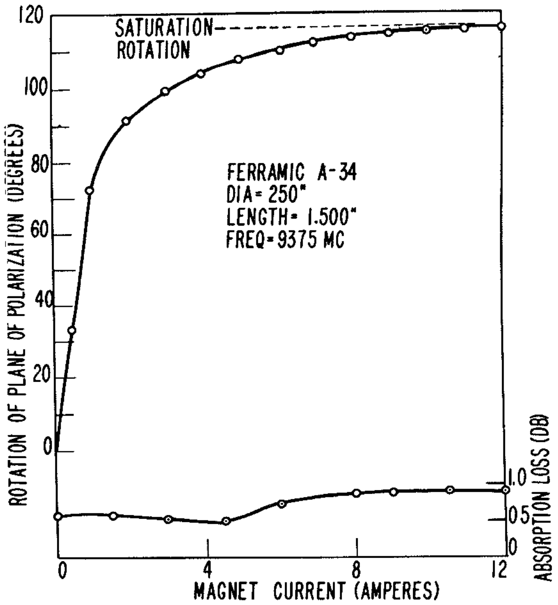

Fig. 1

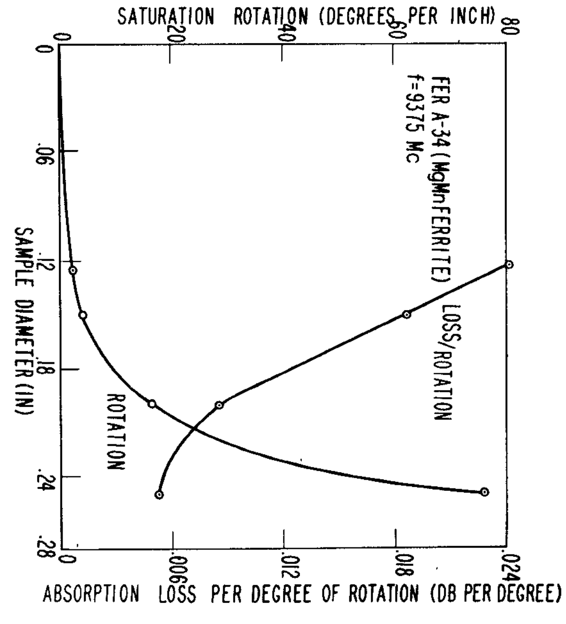

Fig. 2

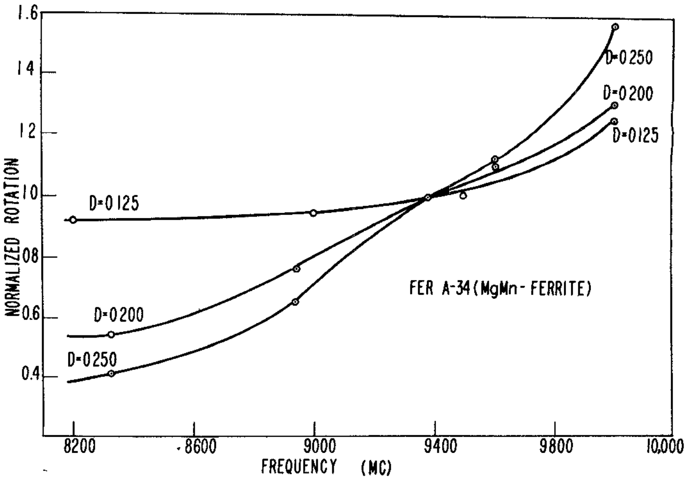

Fig. 3

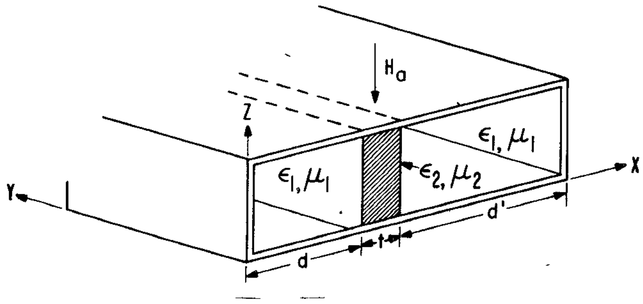

Fig. 4

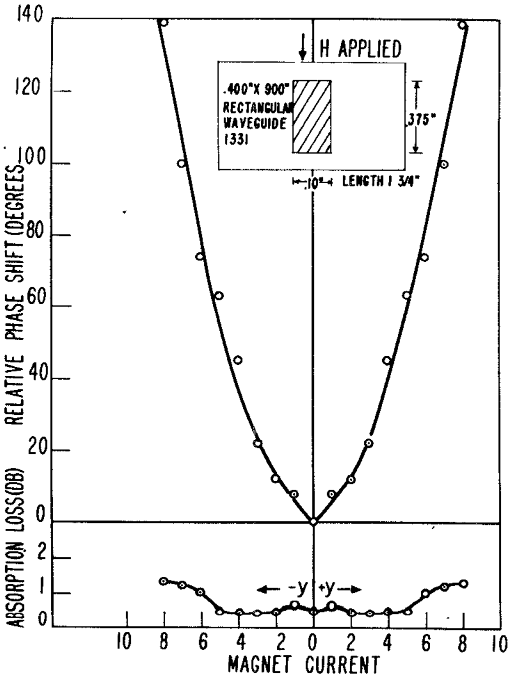

Fig. 5

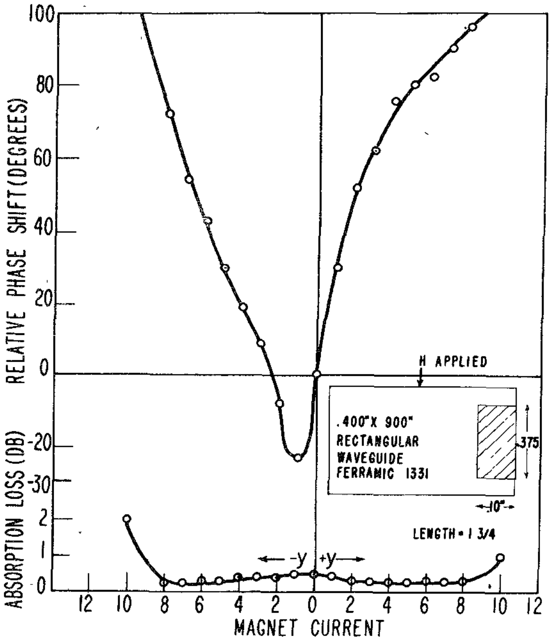

Fig. 6

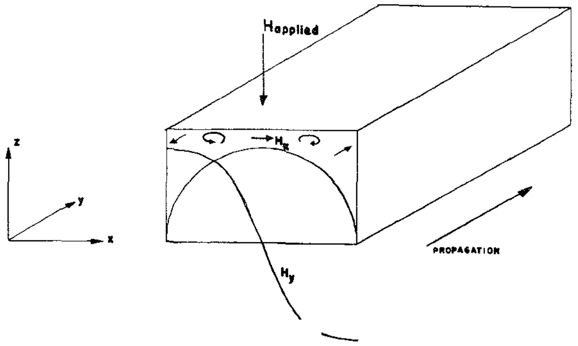

Fig. 7

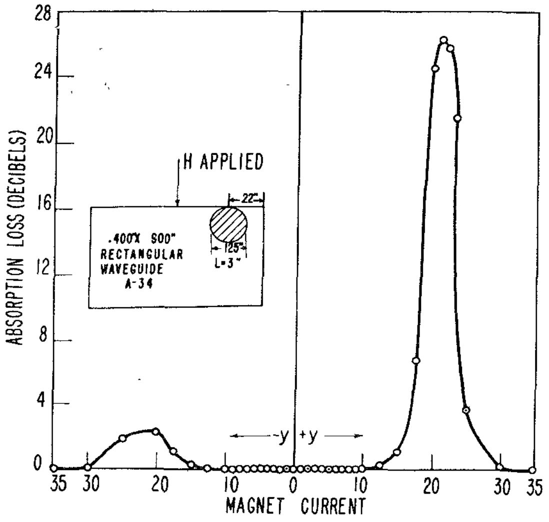

Fig. 8

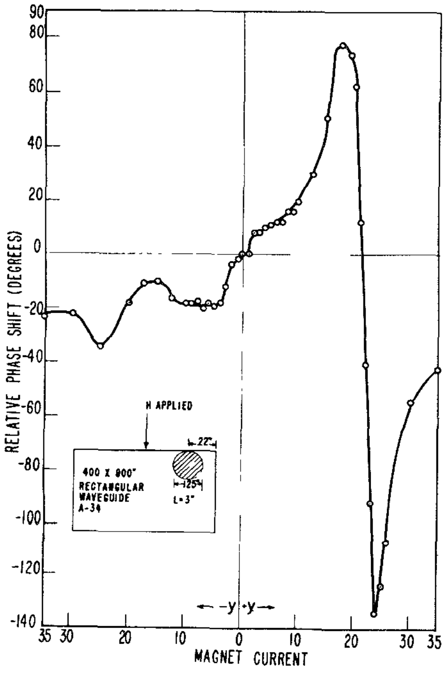

Fig. 9