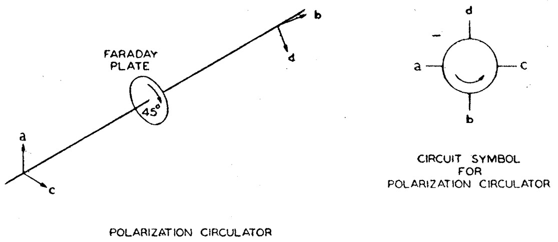

Fig. 13. Schematic diagram of polarization circulator.

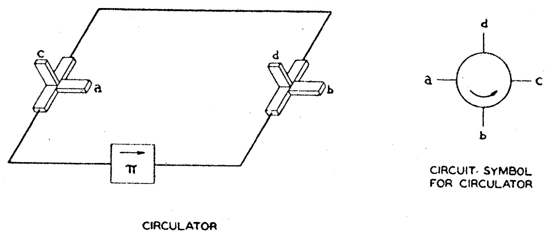

Fig. 14. Schematic diagram of circulator.

power sent into the polarization circulator with polarization *a* is turned into polarization *b*, also *b* is turned into *c*, *c* is turned into *d*, and *d* is turned into *minus a*. This property is indicated very clearly by the circuit symbol suggested in Fig. 13, the phase inversion between arms *d* and *a* being indicated by the minus sign between the *d* and *a* arms.

Another one-way transmission system can be created by combining the gyrator with two magic tees. This combination is indicated in Fig. 14. Since this device has all of the fundamental properties of the polarization circulator with the exception of the phase inversion between arms *d* and *a* it is suggested that it be called a *circulator* and the circuit symbol suggested which indicates its properties is also given in Fig. 14.

This list of applications is obviously not complete since it includes only the fundamental elements from which innumerable specific applications can be made.

In addition to the applications discussed above, which depend upon the antireciprocal property of the element for their operation there are several simple applications which are based only upon the fact that the amount of rotation can be controlled externally by adjusting the magnetic field. Among these uses are electrically controlled attenuators, modulators, and microwave switches.

If a circularly polarized wave is propagated in a circular guide or if the dominant mode is propagated in a rectangular wave guide with the magnetic field being applied along the electric vector of the wave, the above phenomenon allows one to realize externally controlled microwave phase shifters, attenuators, modulators, and microwave windows.

ACKNOWLEDGMENTS

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DISCUSSION

A. G. Fox and M. T. Weiss, *Bell Telephone Laboratories, Holmdel, New Jersey:* As Dr. Hogan has stated, one can apply the plane wave analysis of Faraday rotation, ferromagnetic resonance, and other phenomena in ferrites, only with very great caution to the interpretation of measurements made in ferrite filled wave guides. We would like to describe some of our own experiences in this matter.

1. Mode conversion problem.—Because of the relatively high index of refraction of most ferrites, a dominant mode hollow metal guide, when completely or even partially loaded with a ferrite rod, may be capable of propagating higher order modes. Furthermore, experiments have shown that a pencil of high index of refraction placed in the center of a circular wave guide will have a tendency to convert the dominant TE_{11} mode to the TM_{11} mode.

This mode conversion problem became apparent to us while making measurements in circular guide of loss and ellipticity of large diameter ferrite rods, properly tapered, as a function of magnetic field. The results showed peculiar large variations of these quantitites. We now believe that these variations can be attributed to a partial conversion of the dominant TE_{11} mode to the TM_{11} mode by the ferrite pencil which was of sufficient diameter to permit the propagation of both modes. Thus, as the magnetic field is varied, the permeability changes, causing the electrical length of the line to change, so that the interference between the TM_{11} and TE_{11} modes can vary also.

In order to check the foregoing hypothesis, experiments were performed using circularly polarized waves. As is well known, theory predicts that, for a positively rotating circularly polarized wave, the permeability, μ, of the ferrite starts at unity for zero magnetic field, and then decreases, passes through zero, and goes through resonance as the applied longitudinal magnetic field is increased. For a negatively rotating circularly polarized wave, on the other hand, μ starts at unity, increases until saturation is reached, and finally approaches unity again at very high magnetic fields.

From these considerations it is evident that the negatively rotating component should be more readily subject to mode conversion than the positively rotating component since the former has a higher index of refraction while the latter has an index of refraction which drops sharply with applied magnetic field. Our experiments with circularly polarized waves confirm the foregoing ideas and indicate that the negative component may have many loss peaks and valleys in a plot of loss *vs* applied field, while the positively rotating component has a smooth loss curve at fields below the resonance field value. For small diameter ferrite pencils, which cannot support the higher order modes, no peculiar loss peaks are observed.

2. Ferromagnetic resonance for negatively rotating wave guide mode.—When making circularly polarized wave measurements in wave guides on ferrite pencils thin enough to reduce though not eliminate mode conversion, the usual loss peak for positively rotating waves occurred at a high field value corresponding to ferromagnetic resonance. Surprisingly enough, however, we also observed a loss peak for the negatively rotating waves at magnetic fields very nearly the same as that required to produce ferromagnetic resonance for the positive wave. The magnitude of this negative peak depends on the size of ferrite used, being very small for very thin pencils and reaching values above the loss peak for the positive wave for some larger diameter samples.

It is believed that this effect is connected with the fact that for a wave guide propagating a circularly polarized wave of a given mode, the electric and magnetic field vectors are in general circularly polarized only at the center of the wave guide cross section. Thus, by reference to a field pattern for the TE_{11} mode, it can be seen that near the walls of the guide the transverse component of the rf electric and magnetic vectors is linearly polarized. Therefore, one would expect a small loss peak for negative circularly polarized waves at resonance field values, but this alone would not appear to account for the high loss peak obtained with the larger diameter ferrites.

The high negative wave loss observed in the larger diameter samples can perhaps be attributed to TM_{11} mode propagation. In this mode, when the rf magnetic field vector is circularly polarized in the positive sense in the center of the guide, it is polarized in the opposite sense near the periphery. This is substantiated by the theoretical work of H. Suhl and L. R. Walker (to be published) which shows that the propagation constant of both positively and negatively circular polarized waves are nearly equal in a ferrite filled circular wave guide propagating the TM_{11} mode. For this mode, the ferrite cannot distinguish between a positively or negatively circularly polarized wave. Therefore, one would expect equal loss for the positive and negative wave at the resonance magnetic field value.

However, when one has a mixture of TE_{11} and TM_{11} modes in the ferrite, the negative wave loss may be greater than, equal to, or less than the positive wave loss, depending upon the relative phasing of the two waves. Further work is planned to confirm the above hypothesis.

3. Loss near zero field.—It has long been known that many ferrites have rather large loss at low magnetic fields. With the application of moderate magnetic fields in any direction, longitudinal or transverse, this loss disappears. This strongly suggests that this low field loss may be the result of domain wall motion which disappears upon the application of magnetic field.

If domain wall motion were the cause of this low field loss, one would expect the loss to be independent of the direction of rotation of the circularly polarized wave propagating through the ferrite. However, our experiments on small diameter pencils of ferrite have shown that the loss has a peak for the negatively polarized wave. This rather puzzling asymmetry can be explained by examining the variation of μ with applied field as previously described. It is seen that μ increases for the negatively polarized wave and decreases for the positively polarized wave. Therefore, just as in the case of a dielectric wave guide, there will be a higher concentration of energy in the ferrite when $(\mu\epsilon)^{\frac{1}{2}}$ is larger, that is, on the negatively polarized side rather than on the positively polarized side. Therefore, if the loss peak at zero field in an infinite medium were symetrical with respect to the direction of circular polarization, one would still expect the loss to be higher for negatively rotating waves for a partially filled wave guide. For a fully filled wave guide, the asymmetry should again disappear, but experiments to check this are difficult to interpret because of mode conversion and cavity resonance effects.