The Status of Microwave Applications of Ferrites and Semiconductors*

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Summary—The recent developments in the field of ferrite devices are reviewed. Emphasis is placed on the extension of nonreciprocal devices to lower microwave frequencies and high powers. The design considerations and achievements of broad banding also are covered. Fundamental principles leading to the applications of nonlinear properties of ferrites are described briefly. Preliminary experimental accomplishments in the construction of frequency doublers, mixers, and ferromagnetic resonance amplifiers are summarized. The possible role of the new ferrimagnetic garnet material is indicated. Although no significant new semiconductor devices have been developed at microwave frequencies, possibilities are considered for doing this with use of cyclotron resonance and spin resonance phenomena and their related properties in semiconductors.

Introduction

THIS paper's object is to review the developments in the application of ferrites at microwave frequencies during the last two years. The emphasis is placed on the improvements of existing devices, their extension to lower frequencies, to higher power, and the consideration of broad banding these devices. New developments, such as the ferromagnetic amplifier and nonlinear devices, also are discussed in terms of the basic ideas and research which has led to these new devices. The four devices which have received a great deal of attention are the ones using the Faraday rotation phenomenon, the nonreciprocal phase shifter in rectangular waveguide, the resonance isolator, and the field-displacement isolator. The problems taken up in regard to these devices are the considerations of the principles involved in broad banding and in improving performance at lower frequencies and higher power. Some of these problems have been reviewed in previous articles,[1–8] which have shown that one of the most important problems associated with achieving these objectives is the magnetic losses in the ferrite.

One contribution is the low-field loss in the ferrite when it is in the unmagnetized state. This arises from the existence of internal fields consisting of the effective anisotropy field and the magnetic field induced inside the ferrite by the magnetic charges created on the domain walls by the rf field.

The second type of magnetic loss is that associated with ferromagnetic resonance in the ferrite when it is in the magnetized state. One way to minimize the low-field loss has been offered by the synthesis of diluted ferrites with low magnetization[9] and low anisotropy fields. The residual loss then is negligible in the partially magnetized state, the usual one employed in operating ferrite devices with applied dc magnetic fields below resonance. Another solution for avoiding the low-field loss, suggested by R. H. Fox,[10] is the operation of the ferrite in a completely magnetized state with larger dc fields above resonance. This particular scheme has been employed recently by Stern[11] to build a high-power phase shifter at S band.

The low-frequency limit of the four classes of devices, however, has been determined primarily by the losses attributed to the ferromagnetic resonance phenomenon in ferrites.[7,12] As is indicated later, the important factor which describes the loss at a given frequency is the resonance line width of the ferrite. It is important that the line width be made as narrow as possible in order to reduce the loss associated with ferromagnetic resonance. Considerable effort has been made to develop ferrites which have narrow resonance lines. The most successful results have been achieved with a new ferrimagnetic material called the yttrium-iron garnet. The synthesis of this material has been reported by Bertaut and Forrat[13] and by Geller and Gilleo.[14] The microwave properties of single crystals of this material have been measured

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[1] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications," *Rev. Mod. Phys.*, vol. 25, p. 253; January, 1953.

[2] J. H. Rowen, "Ferrites in microwave applications," *Bell Sys. Tech. J.*, vol. 32, p. 1333; November, 1953.

[3] M. L. Kales, "Propagation of fields through ferrite loaded waveguides," *Proc. Symp. on Modern Advances in Microwave Techniques*, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y., p. 215; November, 1954.

[4] B. Lax, "Fundamental design principles of ferrite devices," *Proc. Symp. on Modern Advances in Microwave Techniques*, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y., p. 229; November, 1954.

[5] A. G. Fox, S. E. Miller, and M. T. Weiss, "Behavior and applications of ferrites in the microwave region," *Bell Sys. Tech. J.*, vol. 34, p. 5; January, 1955.

[6] C. L. Hogan, "The elements of nonreciprocal microwave devices," PROC. IRE, vol. 44, pp. 1345–1368; October, 1956.

[7] B. Lax, "Frequency and loss characteristics of microwave ferrite devices," PROC. IRE, vol. 44, pp. 1368–1386; October, 1956.

[8] P. J. B. Clarricoats, A. G. Hayes, and A. F. Harvey, "A survey of the theory and applications of ferrites at microwave frequencies," *Proc. IEE*, vol. 104 B, p. 267; October, 1956.

[9] L. G. Van Uitert, J. P. Shafer, and C. L. Hogan, "Low-loss ferrites for applications at 4000 megacycles per second," *J. Appl. Phys.*, vol. 25, p. 925; July, 1954.

L. G. Van Uitert, "Low magnetic saturation ferrites for microwave applications," *J. Appl. Phys.*, vol. 26, p. 1289; November, 1955.

[10] R. H. Fox, "Extension of nonreciprocal ferrite devices to the 500–3000 megacycle frequency range," *J. Appl. Phys.*, vol. 26, p. 128; January, 1955.

[11] E. Stern, private communication.

[12] B. Lax, "A figure of merit for microwave ferrites at low and high frequencies," *J. Appl. Phys.*, vol. 26, p. 919; July, 1955.

[13] F. Bertaut and F. Forrat, "Structure des ferrites ferrimagnetiques des terres rares," *Compt. Rend.*, vol. 242, p. 382; 1956.

F. Bertaut and R. Pauthenet, "Crystalline structure and magnetic properties of ferrites having the general formula $5Fe_2O_3\,3M_2O_3$," *Proc. IEE*, vol. 104 B, p. 261; October, 1956.

[14] S. Geller and M. A. Gilleo, "Structure and ferrimagnetism of yttrium and rare earth-iron garnets," *Acta Cryst.*, to be published.

by Dillon and more recently by others.[15] The magnetic properties and crystal structure of this class of ferrimagnetics have been discussed by Bertaut and Pauthenet.[13] The yttrium garnet, which is the first of a series of such materials, is given by

$$Fe_2^{3+} Y_3^{3+} (Fe^{3+}O_4)_3.$$

This formula can be rewritten as

$$\overset{\uparrow}{B_2} L_3 (\overset{\downarrow}{A}\ O_4)_3$$

where A and B are the two different types of lattice sites for the magnetic ions and L represents the large rare-earth ions such as yttrium, gadolinium, etc. The arrows above the A and B ions indicate that the magnetic moments of the two sets of spins are oriented oppositely as in the ferrite which gives rise to a net magnetization, $4\pi M_s \approx 1700$ Gauss. This means that the residual loss in the unmagnetized state in this material has an upper frequency limit of about 5000 mc. The garnet also has a very high resistivity of the order of 10^6 ohm-cm. As Dillon reported, the anisotropy of this material at room temperature from the microwave resonance measurements on a single crystal is approximately 90 oersteds, or about half that of the ferrites. This is another advantage of this material since it further minimizes the residual loss in the unmagnetized state and also is partly responsible for the narrow resonance line in polycrystalline material. The latter has been reported to be as low as 50 oersteds when the garnet is made fairly dense. Finally, some single crystals of yttrium garnet have a very narrow resonance line (below 10 oersteds) at room temperature. Unlike the diluted ferrites, the yttrium garnet, with its smaller resonance line width and anisotropy, has a reasonably high Curie temperature of about 300°C.

Nonreciprocal Devices

The Faraday Rotator

Consider the effect on the Faraday rotator of the development of these new materials which possess narrower resonance lines. The resonance loss parameter enters in the following manner. An idealized limit for the figure of merit F from perturbation theory can be written as[7,12]

$$F = \frac{\theta}{\alpha} = \omega T = \frac{2H_r}{\Delta H}, \tag{1}$$

where F is the ratio of θ, the angle of rotation, to α, the attenuation, and is approximately equal to ω, the angular frequency, times T, the phenomenological relaxation time associated with the precessional motion of the dipole. H_r is the internal field required for resonance at the frequency ω, and ΔH is the width of the resonance line at the half-power point. The relation of (1) indicates that for a given frequency, which fixes H_r, the figure of merit improves as ΔH decreases. Conversely, if the figure of merit is fixed by the system requirements, then one can go to lower and lower frequencies as ΔH becomes smaller. Considering the properties of the garnet, $\Delta H \approx 50$ oersteds for polycrystalline material, the lower frequency limit for the Faraday rotator becomes approximately 1000 mc. If one could obtain single crystals of this material of sufficiently large size, then in principle, the low-frequency limit could be extended down to approximately 200 mc if one assumes $\Delta H \approx 10$ oersteds. Of course, this presupposes the appropriate design considerations which avoid dimensional and other effects observed with single crystal material of required sizes.

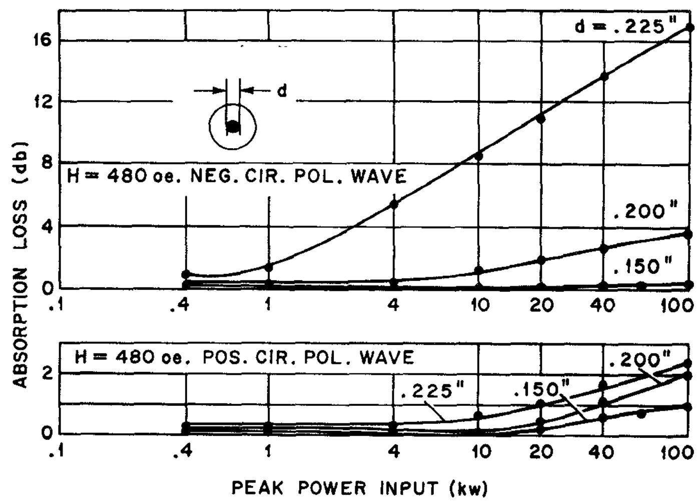

Fig. 1—The absorption loss in a cylindrical waveguide containing a ferrite rod as a function of peak input power for three different diameters of the ferrite rod. The upper figure shows that the absorption of the negative circularly polarized wave increases nonlinearly when the rod diameter is increased. (After Sakiotis, Chait, and Kales.)

The high-power problems in Faraday rotation devices have not been investigated extensively. However, Sakiotis, Chait, and Kales[16] have investigated nonlinear effects in circular waveguide as shown in Fig. 1. The absorption loss increases as a function of peak input power and also becomes larger as the diameter of the ferrite increases. The effect is highly pronounced for the negative circularly polarized wave. It has been demonstrated experimentally by Melchor, Ayres, and Vartanian[17] that under these conditions the microwave energy is concentrated inside the ferrite for this polarization, resulting in large rf fields inside the ferrite. This situation is analogous to that obtained in ferrite spheres

[15] J. F. Dillon, Jr., "Ferrimagnetic resonance in yttrium iron garnet," *Phys. Rev.*, vol. 105, p. 759; January 15, 1957.
C. P. Rodrique, J. E. Pippen, W. P. Wolf, and C. L. Hogan, "Ferrimagnetic resonance in some polycrystalline rare earth garnets," this issue, p. 83.

[16] N. Sakiotis, H. N. Chait, and M. L. Kales, "Nonlinearity of propagation in ferrite media," Proc. IRE, vol. 43, pp. 1011; August, 1955, and "Nonlinearity of microwave ferrite media," IRE Trans., vol. AP-4, pp. 111–115; April, 1956.

[17] J. L. Melchor, W. P. Ayres, and P. H. Vartanian, "Energy concentration effects in ferrite loaded wave guides," *J. Appl. Phys.*, vol. 27, p. 72; January, 1956.

in cavities by Damon[18] and by Bloembergen and Wang;[18] the large losses in these nonlinear effects are associated with instabilities as proposed by Suhl.[19]

A number of schemes has been proposed for broad banding the Faraday rotator. One such scheme, that of surrounding the ferrite rod with a dielectric sleeve, was proposed by Rowen[20] and applied by Ohm[21,22] to develop a broad-band microwave circulator. The effect of such a dielectric sleeve can be seen readily from the results of the perturbation formula which states that the Faraday rotation[7]

$$\theta \sim \sqrt{\epsilon\mu_0 - \frac{(1.84)^2}{\omega^2 R^2}} \tag{2}$$

where θ is the angular frequency of the rf field, R is the radius of the guide, ϵ is the dielectric constant of the medium surrounding the ferrite, and μ_0 is the permeability of free space. As one increases the dielectric constant, the term containing the frequency becomes relatively smaller, making θ less frequency dependent. Perhaps the best scheme for broad banding the Faraday rotator is that suggested by Chait and reported in Kales' review article,[23] in which he used ridged circular waveguide with a ferrite rod down the center. The experiment shows that in the normal waveguide the Faraday rotation increases with frequency, which is also evident from (2). Evidently, the frequency characteristics of the ridged waveguide compensate for the frequency variation of the Faraday rotation from 8000 to 10,000 mc. Melchor and Vartanian[24] and later Wantuch[25] combined both of these schemes using a dielectric sleeve and a ridged waveguide to give a Faraday rotation of 90°±1 per cent from 8.5 to 9.6 kmc. Another very interesting technique for broad banding Faraday rotation devices has been developed by Vartanian, Melchor, and Ayres;[26] this also uses a quadruply ridged circular waveguide and two stagger-tuned Faraday rotators in tandem. The first of these gives a 45° rotation at 9.5 kmc and the second, 45° rotation at 12 kmc, as determined by the applied field to each section. This structure was used

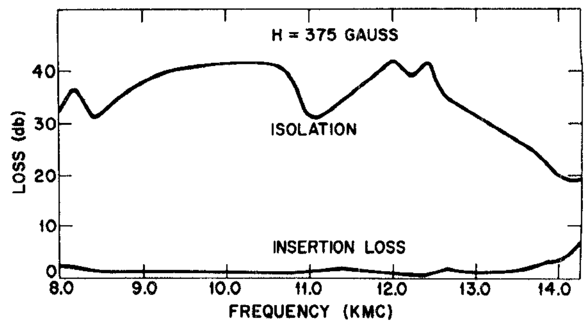

Fig. 2—The reverse and forward attenuation as a function of frequency in a Faraday rotation type isolator which has been broad banded by using both the quadruply ridged circular guide and also two stagger-tuned sections. The two sections were tuned to 9.5 and 12 kmc, respectively. (After Vartanian, Melchor, and Ayres.)

for an isolator, the characteristics of which are shown in Fig. 2. It provides greater than 30-db isolation from 8.2 to 13 kmc with less than 2-db insertion loss.

Rectangular Waveguide Phase Shifter

Some of the considerations discussed for the Faraday rotator apply also to the rectangular waveguide phase shifter. The low-frequency limit, when analyzed quantitatively from the perturbation theory as the ratio of differential phase shift to the total loss, becomes the same numerically as that of the Faraday rotator. Similarly, the high-power considerations as studied by Sakiotis, Chait, and Kales[16] show curves similar to those of Fig. 1 in which the nonlinear losses increase with high power and the thickness of the ferrite slabs used. This phenomenon again is associated with the ferrite dielectric modes, which tend to concentrate the electromagnetic energy in the ferrite slab for one direction of propagation.

Several schemes have been proposed for broad banding the phase shifter. The first of these is that suggested by Fox[4] in which he studied the differential phase shift as a function of the position of the ferrite slab for different frequencies. He showed that the minimum frequency variation would not occur at the position where the differential phase shift was a maximum. Recently, this work has been extended by Van Wolfe and co-workers[27] who optimized this technique. Fig. 3 shows the results of their work for the differential phase shift as a function of frequency for different values of position of the ferrite slab in the waveguide. It can be seen that an extremely small variation of differential phase shift of about $2\frac{1}{2}$ per cent is obtained from 8.2 to 10 kmc when the slab is located 0.150 inch from the wall. Another method proposed by Weisbaum and Boyet[28] uses a ferrite slab on each side of the guide, magnetized in the

[18] R. W. Damon, "Relaxation effects in ferromagnetic resonance," *Rev. Mod. Phys.*, vol. 25, p. 239; January, 1953.
N. Bloembergen and S. Wang, "Relaxation effects in para- and ferromagnetic resonance," *Phys. Rev.*, vol. 93, p. 72; January, 1954.

[19] H. Suhl, "Subsidiary absorption peaks in ferromagnetic resonance at high signal levels," *Phys. Rev.*, vol. 101, p. 1437; February, 1956, and "The nonlinear behavior of ferrites at high microwave signal levels," Proc. IRE, vol. 44, pp. 1270–1284; October, 1956.

[20] J. H. Rowen, "Ferrites in microwave applications," *Bell Sys. Tech. J.*, vol. 32, p. 1333; November, 1953.

[21] E. A. Ohm, "A broad-band microwave circulator," IRE Trans., vol. MTT-4, pp. 210–217; October, 1956.

[22] ——, "A broadband microwave circulator," *Bell. Labs. Rec.*, vol. 35, p. 293; August, 1957.

[23] M. L. Kales, "Propagation of fields through ferrite loaded waveguides," *Proc. Symp. on Modern Advances in Microwave Techniques*, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y., p. 215; November, 1954.

[24] J. L. Melchor and P. H. Vartanian, private communication.

[25] E. Wantuch, private communication.

[26] P. H. Vartanian, J. L. Melchor, and W. P. Ayres, "Broadbanding ferrite microwave isolators," 1956 IRE Convention Record, pt. 5, pp. 79–83.

[27] R. Van Wolfe, C. J. Cacheris, and C. Morrison, "The Broadbanding of Microwave Nonreciprocal Ferrite Phase Shifters," Diamond Ordnance Fuze Labs., Washington, D. C., Rep. No. TR-348; April, 1956.

[28] S. Weisbaum and H. Boyet, "Broad-band nonreciprocal phase shifts—analysis of two ferrite slabs in rectangular waveguide," *J. Appl. Phys.*, vol. 27, p. 519; May, 1956.

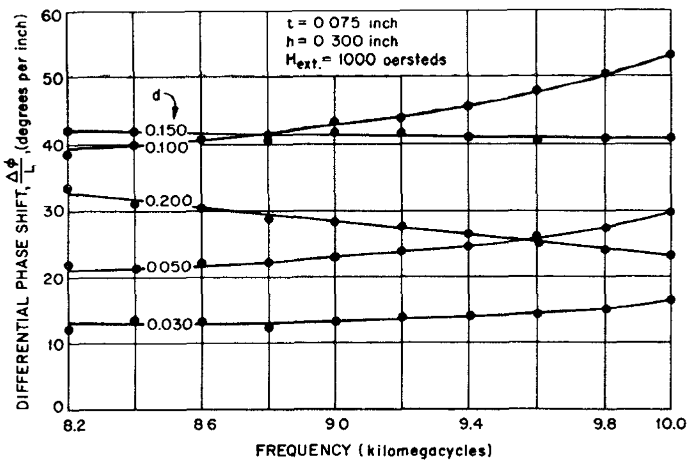

Fig. 3—The differential phase shift as a function of frequency for a transversely magnetized ferrite slab in a rectangular waveguide with the distance, *d*, between the slab and the waveguide wall as a parameter. For a slab 0.075 inch thick placed 0.150 inch from the wall in X-band guide, the differential phase shift is constant within 2.5 per cent over the band. (After Van Wolfe, Cacheris, and Morrison.)

same direction but having different dimensions or magnetic properties. In this case the phase-shift frequency dependences of the two ferrites compensate one another. However, the total differential phase shift is the difference between that of the two ferrites. One can improve on this by operating one of the ferrites above resonance and the other below resonance by using a suitable geometric configuration. In this way, the differential phase shifts of the two ferrites are added and again the frequency variation would compensate. A simple and effective scheme used by Wantuch[25] consists of a ferrite slab and an adjacent dielectric slab, both occupying the full height of the waveguide. As pointed out by Vartanian, Melchor, and Ayres,[26] who use a similar method for a resonance isolator, one of the objectives of using the dielectric is to generate the appropriate elliptical polarization in the region of the ferrite slab adjacent to the dielectric so that the internal field in the ferrite is essentially circularly polarized. The dielectric also minimizes the traversal of the point of circular polarization across the waveguide as a function of frequency. The dielectric loading also minimizes the perturbation in the waveguide due to the presence of the ferrite and reduces the concentration of energy in the ferrite. The optimum position of the slab was determined experimentally,[25] resulting in a 25 per cent bandwidth. The result obtained by dielectric loading of the rectangular waveguide is analogous to that discussed for the Faraday rotator. From the perturbation theory of (2), it was shown that the effect of the dielectric is to broad band the waveguide and to reduce the frequency dependence of the Faraday rotation. Similar arguments show that the same situation is achieved here because, in essence, a dielectric lowers the frequency cutoff of the waveguide and minimizes the shift of the circular polarization of waveguide as a function of frequency. This type of phase shifter, using dielectric loading in rectangular waveguide, has been used in a circulator,[25] which contains two phase shifters between a hybrid-tee junction at one end and a 3-db directional coupler at the other end. The surprising situation is that the ferrite component does not limit the bandwidth of this device but instead the limitation is imposed by the hybrid tee to give a 12 per cent bandwidth in the 9000 mc range with 30-db isolation over the band. This circulator is capable of handling relatively high power of the order of 600 watts average and 600-kw peak.

Resonance Isolators

The resonance isolator has proved to be the most widely used ferrite device at microwave frequencies. In terms of achieving the three objectives of low frequency, high power, and broad bandwidth, the resonance isolator by far is the most successful. First consider the low-frequency problem. In the absence of an exact theory, which is difficult to calculate even for simple geometries, it has been necessary again to resort to the perturbation theory for calculating a theoretical limit for the figure of merit.[7] In this case this is given by the reverse-to-forward loss on resonance or the ratio of the attenuation constant for the negative and positive circularly polarized waves corresponding to the two directions of propagation:

$$R = \frac{\alpha_+}{\alpha_-} = (2\omega T)^2 = \left(\frac{4H_r}{\Delta H}\right)^2. \tag{3}$$

Again ωT, or its equivalent in terms of the resonance line width at the half-power point, determines the lower-frequency limit. To date it has been possible to build this particular type of device at frequencies as low as 1300 mc.[29] With the presently available ferrite materials, Heller[30] also has built an isolator using trough waveguide in the uhf region ($\sim$900 mc) with better than 30 to 1 reverse-to-forward ratio of attenuation.

A number of new techniques has made it possible to improve the figure of merit of the resonance isolator so it approaches the values predicted theoretically. One of the important developments is the dielectric loading introduced by Weiss,[31] who used the scheme of placing a dielectric material adjacent to the ferrite slab, preferably on the inner side. For the *E*-plane isolator in which the long transverse dimension of the ferrite slab is parallel to the electric field in the waveguide, Weiss was able to increase the reverse-to-forward ratio of attenuation from 60 to 1 without the dielectric to about 120 to 1 with the dielectric. Fig. 4 shows the reverse and forward loss as a function of magnetic field for an *H*-plane resonance isolator with and without dielectric loading.

[29] G. S. Heller and G. W. Catuna, "Measurement of ferrite isolation at 1300 mc," this issue, p. 97.

[30] G. S. Heller, "*L*-band isolator utilizing new materials," presented at WESCON Convention, San Francisco, Calif.; August 20, 1957, and Quart. Prog. Rep. on Solid State Res., M.I.T. Lincoln Lab., Lexington, Mass.; August, 1957. (Not generally available.)

[31] M. T. Weiss, "Improved rectangular waveguide resonance isolators," IRE TRANS., vol. MTT-4, pp. 240–243; October, 1956.

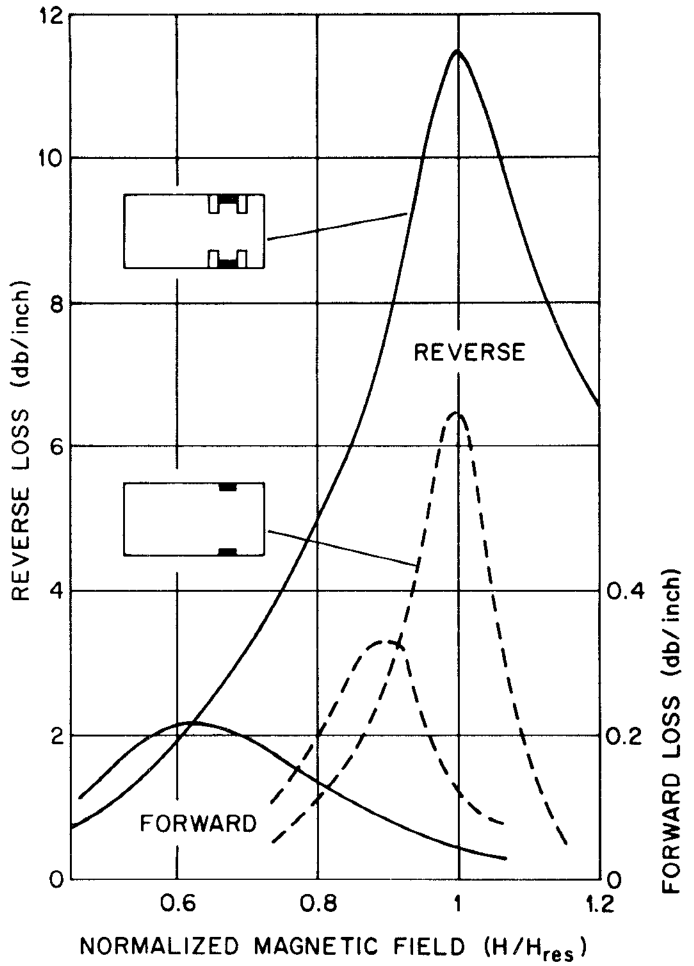

Fig. 4—Experimental curves of the reverse and forward attenuation for a transversly magnetized H-plane ferrite resonance isolator as a function of applied magnetic field. The dashed lines were obtained at a frequency of 10.5 kmc with a flat slab of ferrite placed against the top and bottom walls of X-band waveguide. The solid lines were obtained when dielectric material was placed adjacent to the ferrites as shown in the inset. (From the data of Weiss.)

This time the reverse-to-forward ratio is increased from about 75 to 1 to 150 to 1. This is somewhat better than the E-plane isolator, and one can show from simple reasoning and the analysis of circular polarization in the ferrite and waveguide that this geometry is somewhat more favorable since the position of circular polarization inside the ferrite coincides with that in the waveguide. The importance of dielectric loading and its effect in improving the performance has been demonstrated by Heller[29] in the development of an isolator at 1300 mc, in which he showed progressive improvement in the f gure of merit as he went from partial dielectric loading to a ferrite surrounded by a dielectric.

The progress made in the development of high-power isolators also has been impressive. Wantuch[25] has built an H-plane isolator at about 2800 mc in which four ferrite slabs are located appropriately, two at the bottom, two at the top of the guide on either side of the center. These are surrounded with dielectric in a manner similar to that of Heller's isolator. The dc magnetic field is applied in the opposite sense to the ferrites on the left- and right-hand side of the guide. This scheme provides a compact device which reduces the length of the ferrites to about eight inches. Furthermore, this H-plane configuration gives maximum efficiency for heat transfer from the ferrite to the water-cooled wall of the waveguide. One of the considerations in building a high-power isolator is making the thickness of the ferrite of the order of a skin depth on resonance which is

$$\delta = \frac{\lambda}{2}\sqrt{\frac{2}{\epsilon\omega_M T}} \tag{4}$$

in cgs units. For a ferrite having a saturation magnetization of 2000 Gauss, such as Ferramic $R-1$, the skin depth on resonance at S band is about 1 to 2 mm which turns out to be close to the thickness actually used. This particular unit is capable of handling 4000 watts average power and providing 12-db isolation at this level and a reverse-to-forward ratio of almost 50. The insertion loss is $\frac{1}{4}$ db. This low insertion loss is particularly desirable at these high-power levels.

Several procedures have been proposed for broad banding the resonance isolators. One method, used by Weiss,[31] consisted of two ferrites, one above the other, both magnetized in the same direction and with appropriate dielectric loading. Since the saturation magnetization of the two ferrites differed, the internal fields for the two slabs were unequal resulting in resonance at 10.7 and 11.4 kmc. This combines effectively two resonance isolators which have peak absorption at two frequencies, resulting in the broadening of the reverse-to-forward ratio of better than 40 to 1 over a 10 per cent frequency range. Of course, this scheme has reduced the maximum possible value of R. Such a result is consistent with an approximate relation that $\bar{R}\Delta f \approx$constant, where $\bar{R}$ is the average reverse-to-forward ratio over the frequency range Δf. Thus, in principle, another way of broad banding the resonance isolator, particularly at high frequency, is to select a ferrite with a broad resonance line. Vartanian, Melchor, and Ayres[26] have used dielectric loading adjacent to a thin ferrite slab placed in the E plane of a rectangular waveguide which, for the reasons discussed for the phase shifter, resulted in broad banding the characteristics of the waveguide and of course the resonance isolator. They obtained better than 25 to 1 reverse-to-forward ratio over a band from 8 to 12.5 kmc and, in an S-band isolator, better than 12 to 1 from 2.4 to 4 kmc. Fig. 5 shows results obtained when the two schemes of dielectric loading and stagger tuning are combined.[24,25] This isolator employed two permanent magnets, in tandem, so that the magnetic field applied to two regions of the ferrite differed, providing two resonance frequencies corresponding to the peaks at about 9 and 12 kmc. Experimental location of ferrite and dielectric resulted in 40 per cent bandwidth with a reverse-to-forward ratio greater than 43.

Perhaps one of the most significant recent developments in nonreciprocal devices is the resonance isolator in coaxial waveguide developed by Duncan and co-

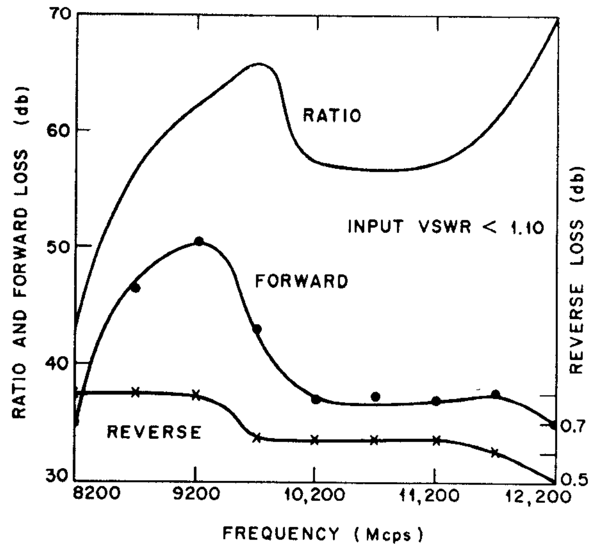

Fig. 5—Experimental curves of the reverse and forward attenuation and reverse-to-forward ratio as a function of frequency for a ferrite resonance isolator. The 40 per cent bandwidth has been achieved by using both dielectric loading and stagger tuning. The two isolators in series were tuned to approximately 9 and 12 kmc, respectively, by applying different external magnetic fields. (From the data of Wantuch.)

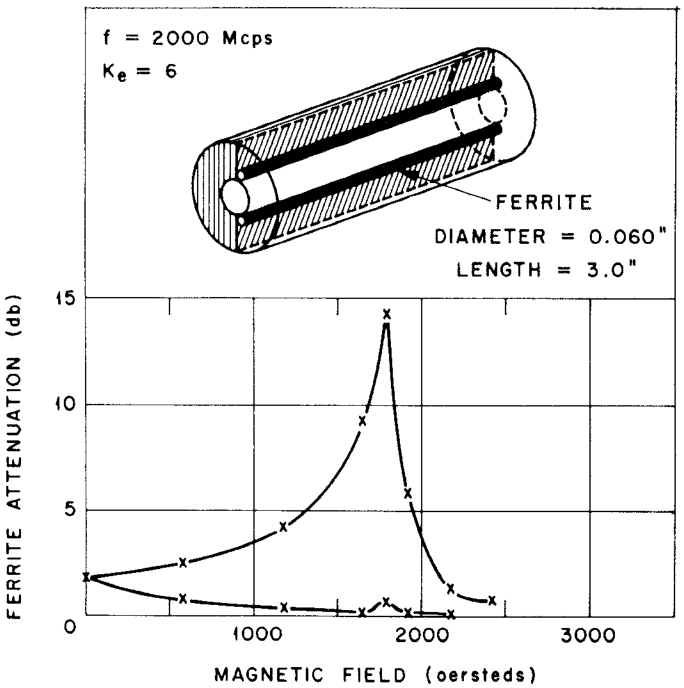

Fig. 6—Attenuation of the positive and negative wave in the S-band coaxial waveguide resonance isolator. The TEM mode of the $\frac{7}{8}$-inch coaxial line has been distorted by half filling the line with the material having a dielectric constant of six. The two small transversly magnetized ferrite rods then provide the nonreciprocal resonant elements. (After Duncan, Swern, Tomiyasu, and Hannwacker.)

workers.[32] This device consists essentially of a transition from an air-filled coaxial line to one which is dielectrically loaded as shown in Fig. 6. In such a device, by proper selection of parameters, one can fill a portion of the waveguide with a dielectric which essentially converts the TEM mode to a quasi-TE mode in which there is no longer any angular symmetry of the fields. Consequently, for the configuration shown, there are two positions of circular polarization of the internal rf field in the ferrite at the dielectric interface. If a transverse magnetic field is applied, a coaxial resonance isolator is possible. This is shown by the attenuation curves for the positive and negative waves shown in Fig. 6. Using this basic idea, Duncan, *et al* were able to build a coaxial isolator with more than 10.5-db isolation over the 2- to 4-kmc band with a forward loss of less than 0.8 db. In addition to broad banding, the coaxial configuration has permitted the construction of very compact devices (~four inches long) at this frequency. Obviously, this new development also offers possibilities of other nonreciprocal devices, such as phase shifters in coaxial geometry. A theory of such a device has been discussed by Sucher and Carlin[33] and also has been considered by the group at Lincoln Laboratory.

The Field-Displacement Isolator

The field-displacement isolator is essentially a low-power device which was first discussed by Fox, Miller, and Weiss.[5] In order to understand the operation of this type of device, two types of configurations have been considered theoretically. One of these is the ferrite slab against the waveguide wall, which the author and Button[34] analyzed in detail, giving a theoretical description of the TE modes in this structure. Button and I predicted nonreciprocal modes, one of which had a field concentrated in the ferrite we described as a ferrite "dielectric mode." The general features of this theoretical analysis have been confirmed experimentally by Straus and Heller[35] for the thick slab against the wall as shown in Fig. 7. They used an electric field probe which traversed across the width of the guide and measured the relative rf electric field intensity as a function of position from the far wall of the guide to the ferrite interface. In the forward direction of propagation for external field intensities of 1000 and 2000 oersteds, they clearly demonstrated the existence of the ferrite "dielectric modes." In the reverse direction of propagation, the electromagnetic field was concentrated in the empty portion of the guide in accordance with the theory. At $H = 3000$ oersteds for the forward direction, there is a departure from the dielectric mode, and the field becomes less concentrated in the ferrite as one approaches

[32] B. J. Duncan, L. Swern, K. Tomiyasu, and J. Hannwacker, "Design considerations for broad-band ferrite coaxial line isolators," Proc. IRE, vol. 45, pp. 483–490; April, 1957.

[33] M. Sucher and H. J. Carlin, "Coaxial line nonreciprocal phase shifters," *J. Appl. Phys.*, vol. 28, p. 921; August, 1957.

[34] B. Lax and K. J. Button, "Theory of new ferrite modes in rectangular waveguide," *J. Appl. Phys.*, vol. 26, p. 1184; September, 1955, and "New ferrite mode configurations and their applications," *J. Appl. Phys.*, vol. 26, p. 1186; September, 1955.

[35] T. M. Straus and G. S. Heller, "Ferrite dielectric mode—experimental," Quart. Prog. Rep. on Solid State Res., M.I.T. Lincoln Lab., Lexington, Mass., p. 50; February, 1956. (Not generally available.)

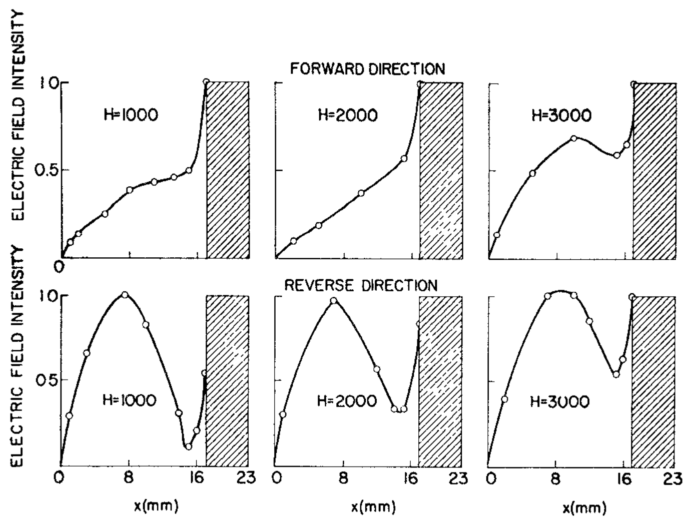

Fig. 7—The experimental electric field configurations in a rectangular waveguide containing a transversly magnetized ferrite slab against the side wall. For an externally applied field of 2000 oersteds at X-band (center figure), the energy is transmitted almost entirely in the ferrite dielectric mode in the forward direction. In the reverse direction, only the distorted waveguide mode exists. (After Straus and Heller.)

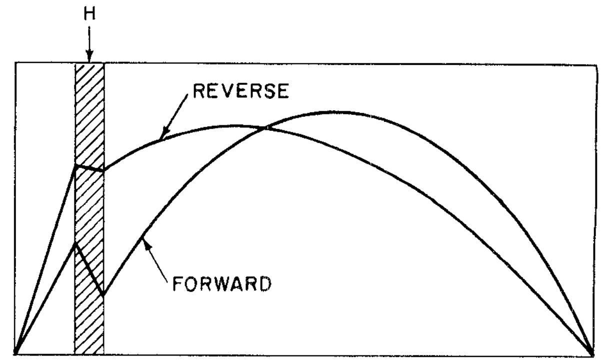

Fig. 8—Theoretical model of the electric field configurations in a ferrite-loaded guide to demonstrate nonreciprocal field displacement. (After Lax, Button, and Roth.)

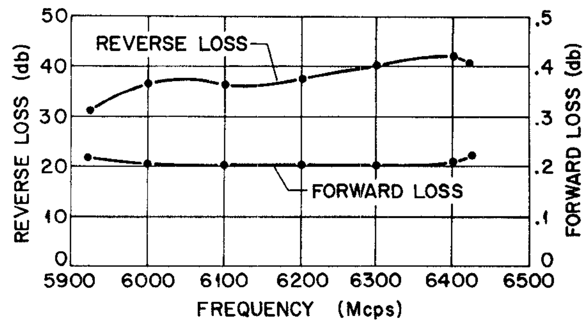

Fig. 9—Experimental curves of the reverse and forward loss as a function of frequency for the single-slab field-displacement isolator. (After Weisbaum and Seidel.)

resonance. This behavior has been demonstrated theoretically by Button.[36]

In analyzing this type of device, the particular electric field configuration used in the literature to explain the principles is that shown in Fig. 8, where a thin ferrite slab is displaced from the wall. The electromagnetic fields for this also have been worked out theoretically[37] and one can show that the null exists for the E field for one direction of propagation.[38] Weisbaum and Seidel[38] carried out their analysis based on this configuration, but their actual device contained a thick slab of ferrite nearly against the wall. Although the analysis used for Fig. 8 predicts the use of a negative effective permeability for the ferrite, the actual experimental devices use the ferrite in a state of positive effective permeability. Button,[39] analyzing this particular case by using the experimental parameters of Weisbaum and Seidel, has shown that the mode configurations for this case are not those of Fig. 8 but, for one direction, involve a "dielectric" mode whose detailed structure has not yet been presented in the literature. The important feature of such a "dielectric" mode is that for one direction of propagation the energy concentration is large within the ferrite and for the other direction it is small. The experimental results of Weisbaum and Seidel definitely involve the existence of two nonreciprocal modes whose field displacement characteristics differ, but their paper does not indicate the nature of the field patterns. Nevertheless, using the empirical approach, they have built such an isolator with a resistance strip or coating across the face of the ferrite whose performance characteristics are shown in Fig. 9. The device operated over the frequency range 5900 to 6400 mc with a reverse-to-forward ratio of attenuation of about 150 to 1 which is better than that achieved by the resonance isolator at this frequency. Weisbaum and Boyet[40] built a field displacement isolator with two ferrite slabs, one on each side of the guide, which were magnetized in the opposite sense. This device had a reverse-to-forward ratio of 70 to 1 from 10.8 to 11.6 kmc and a very low vswr.

A number of other ferrite devices has been developed during the past three years which, although noteworthy, cannot be discussed in detail in this review. The resonance isolator in helical lines was proposed by Cook, Kompfner, and Suhl[41] and further developed by Rich and Webber and also by Enander[42] for use in traveling-wave tubes and related devices. It is not surprising that a phase shifter in a helical line also was developed eventually. A directional coupler using a ferrite was

[36] K. J. Button, "Theory of ferrites in rectangular waveguide," Quart. Prog. Rep. on Solid State Res., M.I.T. Lincoln Lab., Lexington, Mass., p. 47; February, 1956. (Not generally available.)

[37] B. Lax, K. J. Button, and L. M. Roth, "Ferrite phase shifters in rectangular wave guide," *J. Appl. Phys.*, vol. 25, p. 1413; November, 1954.

[38] S. Weisbaum and H. Seidel, "The field-displacement isolator," *Bell Sys. Tech. J.*, vol. 35, p. 877; July, 1956.

[39] K. J. Button, to be published.

[40] S. Weisbaum and H. Boyet, "A double-slab ferrite field displacement isolator at 11 kmc," Proc. IRE, vol. 44, pp. 554–555; April, 1956.

[41] J. S. Cook, R. Kompfner, and H. Suhl, "Nonreciprocal loss in traveling-wave tubes using ferrite attenuators," Proc. IRE, vol. 42, pp. 1188–1189; July, 1954.

[42] J. A. Rich and S. E. Webber, "Ferrite attenuators in helixes," Proc. IRE, vol. 43, pp. 100–101; January, 1955.

B. N. Enander, "A new ferrite isolator," Proc. IRE, vol. 44, pp. 1421–1430; October, 1956.

suggested by Damon[43] and more recently investigated by Berk and Strumwasser.[44] The use of ferrites in cavities for tuning has been treated by Jones, Cacheris, and Morrison,[45] Fay,[46] Nelson,[47] and Burgess,[48] and has been investigated theoretically by Heller and Campbell[49] and Bussey and Steinert[50] for TM modes in a circular cavity containing a cylindrical ferrite rod. The use of ferrites as radiating elements at the end of a waveguide has been discussed by Angelakos and Korman,[51] and ferrites in the form of radiating rods have been described by Reggia, Spencer, Hatcher, and Tompkins.[52] The application of the birefringent properties of ferrites was proposed by Weiss and Fox[53] and has been applied by Karayianis and Cacheris.[54] The single-sideband modulator has been developed for several applications by Cacheris,[55] and switching applications have been discussed by Le Craw.[56] In addition to these, it is important to mention the significant contributions of Seidel[57] in analyzing the anomalous propagation in ferrite-loaded waveguides and their significance in developing new devices and explaining experimentally observed anomalies in existing nonreciprocal components. The possibility of nonreciprocal effects in N-wire transmission lines has been demonstrated theoretically by Boyet and Seidel.[58] Also, attention should be called to the recent reports of Harvey[59] and of Laverick and Rivett-Carnac[60] describing the extension and development of ferrite devices to the millimeter wave region.

Nonlinear Ferrite Devices

Frequency Doublers and Mixers

One of the most interesting developments that promises to provide a new class of devices involving the use of ferrites and related ferrimagnetic materials depends on the nonlinear behavior of the spin system under the action of high rf power. The first of these developments was reported by Melchor, Ayers, and Vartanian,[61,62] who used the ferrite in a waveguide as a frequency doubler to generate power at harmonic frequencies. The phenomenon can be analyzed from the equation of motion of the magnetization vector. This is given in the familiar form

$$\frac{d\vec{M}}{dt} = \gamma(\vec{M} \times \vec{H}) \tag{5}$$

where $\vec{M}$ is the total magnetization, $\vec{H}$ is the total magnetic field, and γ is the gyromagnetic ratio. The total field consists of a dc field and an rf field which can be represented as

$$\vec{H} = \vec{H}_0 + \vec{h}e^{j\omega t}. \tag{6}$$

If the magnetization is written out in a Fourier expansion in the following manner

$$\vec{M} = \vec{M}_0 + \vec{m}_1 e^{j\omega t} + \vec{m}_2 e^{2j\omega t} \tag{7}$$

where $\vec{M}_0$, the dc component of the magnetization is along the direction of the applied dc field, m_1 and m_2 may be determined by substitution of (6) and (7) into (5) and equating terms with the same time dependence. If the resulting equation is linearized no longer, as is usually done in the small-signal theory, then it can be shown that a component of second order along the z direction is given by

$$(\dot{m}_2)_z = \gamma(m_x h_y - m_y h_x) \tag{8}$$

where h_x and h_y are the internal rf magnetic fields within the ferrite in a plane transverse to the dc magnetic field. Obviously, if the rf field is circularly polarized and the first-order magnetization components induced are also circularly polarized, there is no time-dependent z component of the magnetization. However, if either h_x or

[43] R. W. Damon, "Magnetically controlled microwave directional coupler," *J. Appl. Phys.*, vol. 26, p. 1281; September, 1955.
[44] A. D. Berk and E. Strumwasser, "Ferrite directional couplers," Proc. IRE, vol. 44, pp. 1439–1445; October, 1956.
[45] G. R. Jones, J. C. Cacheris, and C. A. Morrison, "Magnetic tuning of resonant cavities and wideband frequency modulation of klystrons," Proc. IRE, vol. 44, pp. 1431–1438; October, 1956.
[46] C. E. Fay, "Ferrite-tuned resonant cavities," Proc. IRE, vol. 44, pp. 1446–1449; October, 1956.
[47] C. E. Nelson, "Ferrite-tunable microwave cavities and the introduction of a new reflectionless, tunable microwave filter," Proc. IRE, vol. 44, pp. 1449–1455; October, 1956.
[48] J. H. Burgess, "Ferrite-tunable filter for use in S band," Proc. IRE, vol. 44, pp. 1460–1462; October, 1956.
[49] G. S. Heller and M. M. Campbell, "Ferrite Loaded Cavity Resonators," presented at Annual PGMTT Meeting, New York, N. Y.; May 9–10, 1957.
[50] H. E. Bussey and L. A. Steinert, "Exact solution for a cylindrical cavity resonator containing a gyromagnetic material," Proc. IRE, vol. 45, pp. 693–694; May, 1957.
[51] D. J. Angelakos and M. M. Korman, "Radiation from ferrite-filled apertures," Proc. IRE, vol. 44, pp. 1463–1468; October, 1956.
[52] F. Reggia, E. G. Spencer, R. D. Hatcher, and J. E. Tompkins, "Ferrod Radiator Systems," Diamond Ordnance Fuze Labs., Washington, D. C., Tech. Rep. No. 357; June, 1956.
[53] M. T. Weiss and A. G. Fox, "Magnetic double refraction at microwave frequencies," *Phys. Rev.*, vol. 88, p. 146; October, 1952.
[54] N. Karayianis and J. C. Cacheris, "Birefringence of ferrites in circular waveguide," Proc. IRE, vol. 44, pp. 1414–1421; October, 1956.
[55] J. C. Cacheris, "Microwave Single-Sideband Modulator Using Ferrites with Transverse Magnetic Fields," Natl. Bur. of Standards, Washington, D. C., Rep. No. 17-77; September, 1952, and "Microwave single-sideband modulator using ferrites," Proc. IRE, vol. 42, pp. 1242–1247; August, 1954.
J. C. Cacheris and H. A. Dropkin, "Compact microwave single-sideband modulator using ferrites," IRE Trans., vol. MTT-4, pp. 152–155; July, 1956.
[56] R. C. LeCraw, "High-speed magnetic pulsing of ferrites," *J. Appl. Phys.*, vol. 25, p. 678; May, 1954.
R. C. LeCraw and H. B. Bruns, "Time delay in high-speed ferrite microwave switches," *J. Appl. Phys.*, vol. 26, p. 124; January, 1955.
[57] H. Seidel, "Anomalous propagation in ferrite-loaded waveguide," Proc. IRE, vol. 44, pp. 1410–1414; October, 1956.
[58] H. Boyet and H. Seidel, "Analysis of nonreciprocal effects in an N-wire ferrite-loaded transmission line," Proc. IRE, vol. 45, pp. 491–495; April, 1957.
[59] A. F. Harvey, "Ferrite structures for millimetre wavelengths," *Proc. IEE*, vol. 104 B, p. 346; October, 1956.
[60] E. Laverick and A. Rivett-Carnac, "Some measurements and applications of the microwave properties of a magnesium-manganese ferrite in the 8–9 mm waveband," *Proc. IEE*, vol. 104 B, p. 379; October, 1956.
[61] J. L. Melchor, W. P. Ayres, and P. H. Vartanian, "Microwave frequency doubling from 9 to 18 kmc in ferrites," Proc. IRE, vol. 45, pp. 643–646; May, 1957.
[62] W. P. Ayres, P. H. Vartanian, and J. L. Melchor, "Frequency doubling in ferrites," *J. Appl. Phys.*, vol. 27, p. 188; February, 1956.

h_y are zero, *i.e.*, the transverse rf field is linearly polarized, then there is a second-order component of m_z which represents the nutational component of the precession at twice the frequency of the applied rf field. One can solve this particular problem directly. However, the expansion scheme used demonstrates the frequency doubling phenomenon rather simply. Furthermore, more complicated situations can be analyzed and interpreted physically by this scheme. Pippin[63] has shown that one can obtain frequency mixing in a manner analogous to the frequency doubling. He used two transverse components of the rf field of different frequencies and the nutational component along the z direction can contain either the sum or the difference frequencies. This situation has been analyzed in detail by Stern and Pershan[64] for both the frequency doubler and the ferrite mixer. They also carried out an experiment in which they demonstrated the mixing phenomenon. At relatively low power levels, of the order of milliwatts, they obtained a conversion factor of about -30 db. It is very likely one can obtain greater efficiency at higher power levels. This was precisely the situation achieved by Melchor, Ayres, and Vartanian,[61] who went up to levels of about 30 kw and obtained a conversion efficiency of about -6 db as indicated in Fig. 10. They carried out their experiments at a peak power level of 30 kw at 9 kmc and obtained 8-kw output at 18 kmc.

Ferromagnetic Resonance Amplifier

A relatively new device proposed by Suhl[65] is a ferromagnetic resonance amplifier based on two classes of phenomena in ferrites recently investigated.[66–71] The first of these involves the theoretical interpretation[67] of the observed behavior of ferrites at high powers as investigated by Damon[18] and Bloembergen and Wang.[18] They observed that the susceptibility at high powers was reduced as the power was increased and, concurrently, that the line width became broader as a function of power, indicating an increased loss. They also observed a secondary absorption peak below resonance at

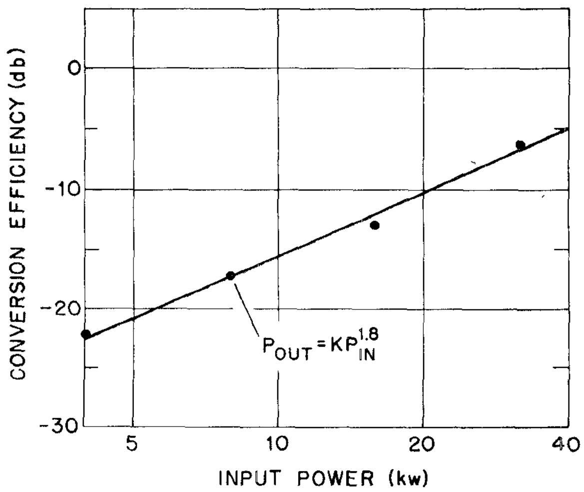

Fig. 10—Conversion efficiency for frequency doubling from 9 to 18 kmc as a function of input power level. These data were taken for a transversly magnetized half disk of ferrite against the side wall of a rectangular waveguide. (After Melchor, Ayres, and Vartanian.)

high powers. Actually, the onset of these effects occurred at relatively low or intermediate power levels, and they are closely related to the effects observed in a waveguide by Sakiotis, Chait, and Kales.[16] The interpretation of these phenomena was given by Suhl, who showed that the onset can occur at these intermediate power levels because of the existence there of an instability of the nonlinear behavior of ferrites. Suhl[67] also has shown that this instability can be represented very simply for a flat disk by the solution of the z component of the magnetization given approximately by

$$\frac{M_z}{M_0} \approx 1 - \frac{\frac{1}{2}\gamma^2 h^2 rf}{[\omega - \gamma(H - N_z M_z)]^2 + 1/T^2} \qquad (9)$$

where M_0 is the total magnetization which is equal to M_z in the absence of an rf signal, $N_z M_z$ is the demagnetizing field in the z direction, and T is a phenomenological relaxation time inversely proportional to the line width. It can be shown from (9) that, below resonance, when the rf power increases, the precessional angle of the magnetization increases, thus decreasing M_z, the component of the magnetization along the direction of the dc magnetic field. This makes $H_{eff} = H - N_z M_z$ larger since the demagnetizing term is smaller, reducing the magnitude of the term in the brackets. Hence, one can see from (9) that M_z on the left-hand side is reduced further. In this way, the effective field is brought even closer to resonance. There is a critical value of the rf field which leads to feedback or an instability of this type. Basically, this phenomenon is responsible for the rapid development of these nonlinear effects at intermediate power levels. As a matter of fact, Suhl has shown[67] that the critical field for this condition is given by

$$h_{crit} \approx \Delta H \sqrt{\frac{3\Delta H}{4\pi M}}. \qquad (10)$$

[63] J. E. Pippin, "Frequency doubling and mixing in ferrites," Proc. IRE, vol. 44, pp. 1054–1055; August, 1956, and Harvard Univ. Gordon McKay Lab., Cambridge, Mass., Sci. Rep. No. 2, AFCRC-TN-369; May, 1956.

[64] E. Stern and P. Pershan, "Harmonic Generation in Ferrites," presented at Symposium on the Role of Solid State Phenomena in Electric Circuits, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y.; April 23, 1957.

[65] H. Suhl, "Proposal for a ferromagnetic amplifier in the microwave range," *Phys Rev.*, vol. 106, p. 384; April, 1957.

[66] P. W. Anderson and H. Suhl, "Instability in the motion of ferromagnets at high microwave power levels," *Phys. Rev.*, vol. 100, p. 1788; December, 1955.

[67] H. Suhl, "The nonlinear behavior of ferrites at high microwave signal levels," Proc. IRE, vol. 44, pp. 1270–1284; October, 1956

[68] ——, "The theory of ferromagnetic resonance at high signal powers," *J. Phys. Chem Solids*, vol. 1, p. 209; January, 1957.

[69] R. L. White and I. M. Solt, "Multiple ferromagnetic resonance in ferrite spheres," *Phys. Rev*, vol. 104, p. 56; October, 1956.

[70] L. R. Walker, "Magnetostatic modes in ferromagnetic resonance," *Phys. Rev.*, vol. 105, p. 390; January, 1957.

[71] J. F. Dillon, Jr., "Ferromagnetic resonance in thin discs of manganese ferrite," *Bull. Amer. Phys. Soc.*, ser. II, vol. 1, p. 125; March, 1956.

Such a condition can also exist when the ferrite sample is spherical and involves the existence of spin waves. Since that subject is beyond the scope of this paper, it is sufficient to give the final result for the sphere. The expression for h_{crit} is similar to (10) except that the factor 3 is replaced by the number 2 in the formula for the critical field for the onset of instability. The significance of this work is that values of the critical field $h_{crit} \approx 8$ oersteds are obtained for a ferrite resonance line width of 50 Gauss. Obviously, the critical value becomes lower as the line width decreases. Suhl's analysis also brought out that the susceptibility of a subsidiary absorption peak below the main resonance increased rapidly above the threshold rf field to a maximum susceptibility and subsequently decreased with increasing power. The physical origin of the increased line width with high power above the threshold has to do with the transfer of energy from the usual uniform precessional mode to spin waves whose frequencies are degenerate with the resonant frequency of the particular geometry associated with the uniform precession.

Another phenomenon which must be considered in this ferromagnetic amplifier and which also is related to the spin waves of a low wave number is that discovered by White and Solt[69] and also investigated experimentally by Dillon,[71] namely, the existence of nonuniform precessional modes in a ferrite body of finite size. Fig. 11 shows some of the original results of White and Solt, in which they placed a ferrite sphere in a cavity where the rf magnetic field is not uniform. Under these circumstances, one obtains resonance in the ferrites containing a number of peaks in addition to the main peak. The figure shows four, although Dillon has obtained many more in his experiments. The explanation is seen in the following: there is a spatial distribution of the precessional phase of the spins in the sphere, such that the magnetic dipoles set up on the surface result in a demagnetization in which there is an azimuthal and a polar distribution as well as a radial distribution in the spins. These were analyzed by Mercereau and Feynman[72] and more completely by Walker.[70]

Suhl has proposed that one can use these magnetostatic modes and the nonlinear properties of the ferrites to build an amplifier in one of three ways. The first one involves the coupling of two nonuniform modes of operation of the ferrite through the uniform precession or the lowest mode of precession of the spins in the ferrite. This requires the condition $\omega_1+\omega_2=\omega$, where ω_1 is the frequency of one of the nonuniform or magnetostatic modes, ω_2 is another, and ω is the operating frequency of the uniform precession. The magnetostatic modes are confined to the range of frequencies $\gamma(H-4\pi M)$ to $\gamma(H+2\pi M)$. This particular system may have some difficulties because of the type of instability discussed previously. A second method involves the use of the resonant properties of a cavity and the magnetic modes of the ferrite as follows. The magnetic field is adjusted such that the frequency of no two nonuniform modes add to ω. However, the resonance frequencies ω_1 and ω_2 of the cavity do add to ω. The sample is placed at a position in the cavity where one of the cavity modes has an rf component along the dc magnetic field and the other cavity mode has an rf component transverse to the dc magnetic field. Suhl calls this the "electromagnetic" scheme in which the ferrite couples the modes of the cavity. The third scheme, which is called "semistatic" operation, is a hybrid of the first two. The cavity could supply one mode, ω_1 and the sample, the other, ω_2. In the first system, the critical or threshold field depends on the sample losses. The electromagnetic scheme depends on the cavity losses or the Q of each cavity mode. In the third case, the threshold field depends on both the cavity and the sample losses. The detailed analysis has not yet been presented in the literature. Very recently, Weiss reported[73] on the operation of such a ferromagnetic resonance amplifier and oscillator. He used the "electromagnetic" mode of operation in which the frequencies f_1 and f_2 were both equal to 4500 mc and the pumping, or resonance, frequency was equal to the sum, 9000 mc. The device achieved a gain of 8 db at the lower frequency as an amplifier and yielded 100 watts peak power output as an oscillator. A single crystal of manganese ferrite was used and the high-power source of pumping power was a magnetron which operated at a level of 20-kw peak for oscillation.

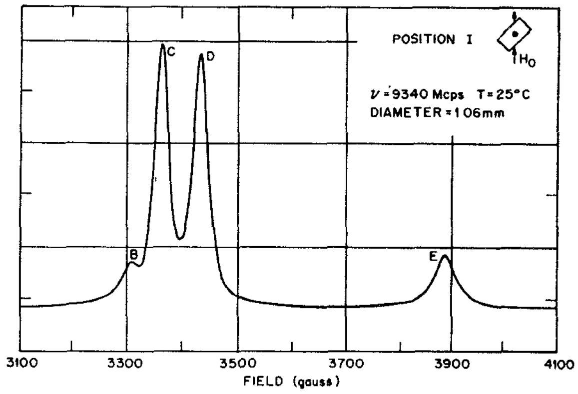

Fig. 11—Multiple ferromagnetic resonances in a single crystal of manganese-zinc ferrite due to nonuniform precessional modes. The ferrite sphere was placed in a cavity in a position of nonuniform rf magnetic field. (After White and Solt.)

Again, in these new devices as well as the old ones, it is desirable to obtain ferrites with narrow resonance line widths. It seems that in both linear and nonlinear devices the operation is enhanced when this is achieved. Hence, the search for new and better materials such as the garnets is an increasingly important aspect of the development of ferromagnetic devices.

[72] J. E. Mercereau and R. P. Feynman, "Physical conditions for ferromagnetic resonance," *Phys. Rev.*, vol. 104, p. 63; October, 1956.

[73] M. T. Weiss, "Microwave ferromagnetic amplifier and oscillator," *Phys. Rev.*, vol. 107, p. 317; July, 1957.

Semiconductors at Microwave Frequencies

The role of semiconductors in microwaves is not new as the first microwave rectifiers built during World War II were made of either silicon or germanium. Not a great deal of development work has been done to improve and extend the use of semiconductors as microwave detectors until recently when Messenger and McCoy[74] took advantage of the know-how obtained from the transistor technology and used single germanium crystals of appropriate resistivity to optimize the properties of microwave detectors at selected frequencies. The possible use of such detectors at low temperatures is receiving some attention and perhaps with the greater understanding of semiconductors which has been achieved, some progress may be made in this direction. The use of the *p-n* junction diode, particularly the depletion layer as proposed by Gärtner,[75] narrow-base devices, graded base diodes, and transistors shows promise of application at higher frequencies, which probably will extend into the microwave region.

The primary reason for including semiconductors in this review is to discuss the close relationship to the behavior of ferrites in electromagnetic fields, which has led to nonreciprocal devices and resonance amplifiers. It is this feature of semiconductors and the two classes of phenomena, namely cyclotron and spin resonance in semiconductors, that is discussed next.

Cyclotron Resonance

The initial experiments have been carried out at Berkeley and at Lincoln Laboratory.[76–78] This phenomenon is a simple one and involves the motion of an electron or a hole in the semiconductor in the presence of a dc magnetic field. One can write very simple equations of motion for such a charged particle as follows:

$$m^*\dot{\vec{v}} = e\vec{E} \exp(j\omega t) + e(\vec{v} \times \vec{B}) \tag{11}$$

where $\vec{B}$ is the dc magnetic field and m^* is the effective mass which is usually less than that of the free electron mass, m_0. In materials such as InSb where the electron mass is isotropic and represented by a simple scalar quantity, the problem is very similar to that which occurs in the propagation of electromagnetic waves in an ionized gas. This equation can be solved readily to obtain an expression for the conductivity tensor that is very similar to the form of representation of the permeability tensor for ferrites. For the case of interest here the conductivity tensor can be represented in the following form:

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & 0 \\ -\sigma_{12} & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{bmatrix}. \tag{12}$$

These tensor components are given by

$$\sigma_{11} = \sigma_{22} = \sigma_0 \frac{1 + j\omega t}{(1 + j\omega\tau)^2 + (\omega_c\tau)^2}$$

$$\sigma_{12} = -\sigma_{21} = \sigma_0 \frac{\omega_c\tau}{(1 + j\omega\tau)^2 + (\omega_c\tau)^2}$$

$$\sigma_0 = \frac{ne^2\tau}{m^*} \tag{13}$$

where τ is the mean free time of scattering of a charge carrier, e is the electronic charge, n is the number of charge carriers per cubic meter, and $\omega_c = eB/m^*$ is the cyclotron resonance frequency. To show the analogy between the permeability of ferrites and conductivity of semiconductors, examine the plot in Fig. 12(a) of the scalar permeability quantities used for the positive and negative circular polarized fields. The dispersive and dissipative components are shown in the familiar forms used to explain the basic operation of nonreciprocal devices. For instance, for the Faraday rotation, the dispersive components which are the real parts of the susceptibilities are used below resonance where the differential effects are greatest. The conductivities for circularly polarized waves propagating through a semiconductor are given by $\sigma_\pm = \sigma_{11} \pm \sigma_{12}$ where the complex quantities σ_{11} and σ_{12} are given in (13). The real and imaginary parts of $\sigma_\pm$ have been plotted in Fig. 12(b). In this case, however, the dispersive components are the imaginary parts and exhibit maximum differential effects above resonance. Hence, a device using the Faraday rotation in a semiconductor probably should be operated at values of applied magnetic field above resonance. It is likely this is the most practical type of nonreciprocal device that can be built with semiconductors, because circularly polarized rf electric fields are not obtained very conveniently except in square or circular waveguide. It is evident from Fig. 12(b) that the resonance properties (again in a cylindrical waveguide) could be utilized for constructing a nonreciprocal resonance isolator. This may have some possible advantages over the ferrite isolator at very high microwave frequencies. Firstly, the rotation or absorption per unit volume in a semiconductor can be much larger because the interaction of a single electron with the electric field is much greater than that of a single magnetic dipole with the rf magnetic field by a factor of 10^{13}.

[74] G. C. Messenger and C. T. McCoy, "A Low Noise-Figure Microwave Crystal Diode," Philco Corp., Philadelphia, Pa., unpublished report.
C. T. McCoy, "The 1N263, A Low-Noise Microwave Mixer Diode," presented at Electronic Components Conference, Los Angeles, Calif.; May 26, 1955.

[75] W. W. Gärtner, "Transit Time Effects in Depletion Layer Transistors at Microwave Frequencies," presented at Symposium on the Role of Solid State Phenomena in Electric Circuits, Polytechnic Inst. of Brooklyn, Brooklyn, N. Y.; April 23, 1957.

[76] See, for example, the review of work on silicon and germanium by G. Dresselhaus, A. F. Kip, and C. Kittel, "Cyclotron resonance of electrons and holes in silicon and germanium crystals," *Phys. Rev.*, vol. 98, p. 368; April, 1955.

[77] R. N. Dexter, H. J. Zeiger, and B. Lax, "Cyclotron resonance experiments in silicon and germanium," *Phys. Rev.*, vol. 104, p. 637; November, 1956.

[78] For a recent review of cyclotron resonance and tabulated data on a variety of semiconductors and metals, see B. Lax, "Experimental investigations of the electronic band structure of solids," *Rev. Mod. Phys.*, January, 1958.

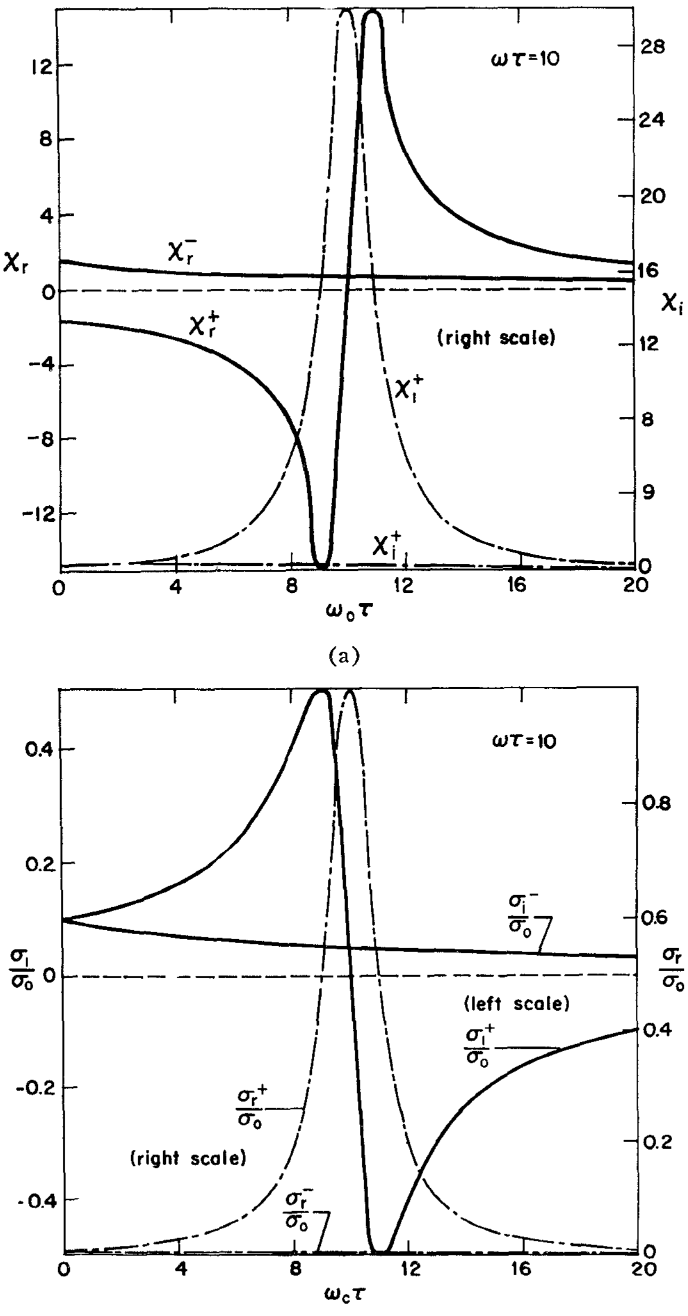

Fig. 12—Components of (a) complex scalar susceptibility and (b) conductivity for the positive and negative circularly polarized waves as a function of applied dc magnetic field. The resonances shown are ferromagnetic and cyclotron resonance, respectively.

Although the number of electrons per unit volume may be less, nevertheless the over-all effect is much greater. The same considerations of line width apply to the semiconductor as to the ferrite. The value of $\omega\tau = 10$ shown in Fig. 12(b) represents that obtained for a pure sample of germanium that could only be achieved at liquid helium temperature and at K-band frequency (or possibly millimeter waves at liquid nitrogen temperature). However, there is an additional definite advantage over the ferrites in the millimeter region because the effective mass of holes and electrons are much smaller than the free electron mass. In germanium the electron mass is about 0.1 m_0 and the light hole mass is about 0.04 m_0; in InSb the electron mass is about 0.013 m_0. This means that cyclotron resonance can be observed in germanium with 4-mm radiation using a dc magnetic field of only 2500 Gauss or 1000 Gauss for n type or p type, respectively. In indium antimonide, only the fairly small field of 400 Gauss would be required.

Germanium is most desirable from the point of view of getting the highest value of $\omega\tau$. At the present time it is not really a very simple medium from the electromagnetic viewpoint. The cyclotron resonance phenomenon has shed a great deal of light on this and Fig. 13 shows just how complicated the situation is. If one orients the magnetic field arbitrarily relative to the crystalline axis, then for the electrons, one can obtain four resonances. This is because there are four sets of electrons, each moving on an ellipsoidal energy-momentum surface, which are directed along the four cube diagonals of the cubic crystal. Thus for n-type material, it is necessary that one direct the magnetic field along the cube axis, in which case all of the electrons appear identical and one obtains only one resonance value. The situation is different for p-type material. There are two kinds of holes, a heavy hole and a light hole. The light hole is nearly isotropic, has a mass of 0.04 m_0, and is less densely populated than the heavy hole which has a mass of $\sim$0.33 m_0. The latter moves on an energy-momentum surface, which is a warped sphere giving rise to nonlinear effects in the presence of a magnetic field. Dexter, Zeiger, and Lax[71] have observed second and third harmonics of the heavy hole resonance due to the existence of warping. Maiman[79] has suggested the possibility of harmonic generation by modulating the cyclotron resonance frequency with an alternating magnetic field.

The electromagnetic problems have been treated, taking into account the complicated anisotropy properties of either the holes or electrons, and the results have been expressed in terms of an effective conductivity which is defined by[80]

$$\Gamma^2 = -\omega^2\epsilon\mu_0 + j\omega\mu_0\sigma_{\text{eff}}. \tag{14}$$

The expressions for σ_{eff} for electrons in germanium and silicon have been worked out by Lax and Roth[80] for different orientations of the dc magnetic field and for various electric field polarizations. The simplest is the case where the dc field is parallel both to the direction of propagation and, for germanium, to the cubic or [100] axis of the crystal. In the case of silicon, the magnetic field and the propagation vector should be along the cube diagonal or [111] axis. Then, for both germanium and silicon

$$\frac{\sigma_{\text{eff}}}{\sigma_0} = \frac{1 \pm (\rho + 2)jb/(2\rho + 1)}{1 + (\rho + 2)b^2/3\rho} \tag{15}$$

[79] T. H. Maiman, "Solid State Millimeter Wave Generation Study—Second Quarterly Progress Report," Hughes Aircraft Co., Culver City, Calif.; October–December, 1956.

[80] B. Lax and L. M. Roth, "Propagation and plasma oscillation in semiconductors with magnetic fields," *Phys. Rev.*, vol. 98, p. 548; April, 1955

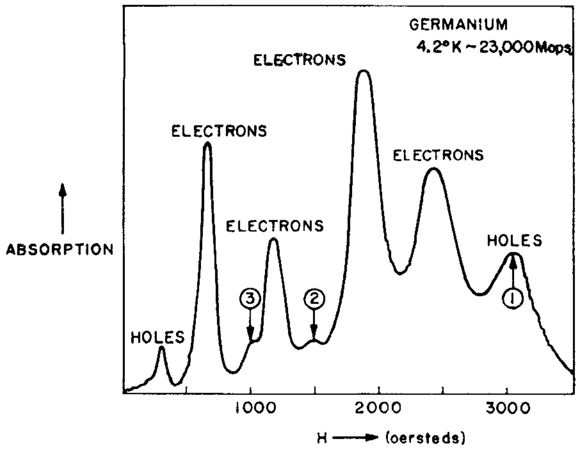

Fig. 13—Experimental cyclotron resonance absorption in germanium at K band and liquid helium temperature as a function of magnetic field. Resonance peaks for the electrons and holes are indicated. (After Dexter, Zeiger, and Lax.)

where

$$\sigma^* = ne^2/m^*(\nu + j\omega),$$
$$m^* = 3m_l m_t/(2m_l + m_t),$$
$$b = eB/m_t(\nu + j\omega),$$
$$\rho = m_l/m_t.$$

σ^* is the rf conductivity in the absence of a magnetic field; m^* the average or conductivity mass expressed in terms of the longitudinal mass m_l and the transverse mass m_t associated with the ellipsoidal energy surfaces; and b is a parameter which is proportional to the magnetic field and involves the collision frequency ν, which is assumed independent of electron energy. The difference between silicon and germanium is that $m_l = 1.64\ m_0$, $m_t = 0.082\ m_0$ for germanium, and $m_l = 0.98\ m_0$, $m_t = 0.019\ m_0$ for silicon. Analogous results for the holes, taking into account the warped surfaces, have been worked out by the Lincoln group for various limiting conditions.

Spin Resonance

The first spin resonance experiments in semiconductors were observed first by the group at Berkeley,[81] which studied the spin resonance in heavily doped n-type silicon, as shown in Fig. 14. An apparent single line was observed in which the line width varied as a function of temperature from about 2 oersteds at liquid helium to about 30 oersteds at room temperature. Since then more extensive work has been carried out, primarily at Bell Laboratories, in which different impurities and different concentrations were used. At high impurity concentrations, one obtains an apparent single line. However, it is shown in Fig. 15 that[82] at lower concentrations, one can observe the splitting due to the presence of the nucleus, *i.e.*, the hyperfine structure, which becomes more complex as the magnetic moment of the nucleus increases from $\frac{1}{2}$ in phosphorus to $\frac{3}{2}$ in arsenic to $\frac{5}{2}$ and $\frac{7}{2}$ in antimony. The narrow lines obtained in these materials indicate interesting possibilities. Furthermore, the very long spin-lattice relaxation times, of the order of seconds as observed by Feher

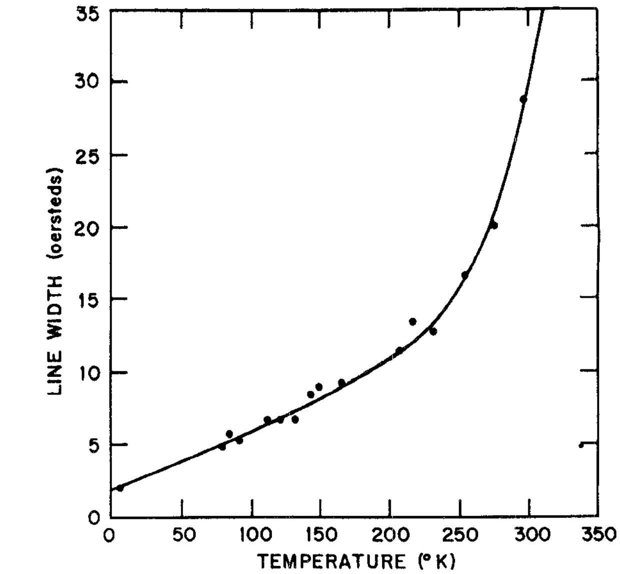

Fig. 14—Electron spin resonance line width in n-type silicon at X band as a function of temperature. (After Portis, Kip, Kittel, and Brattain.)

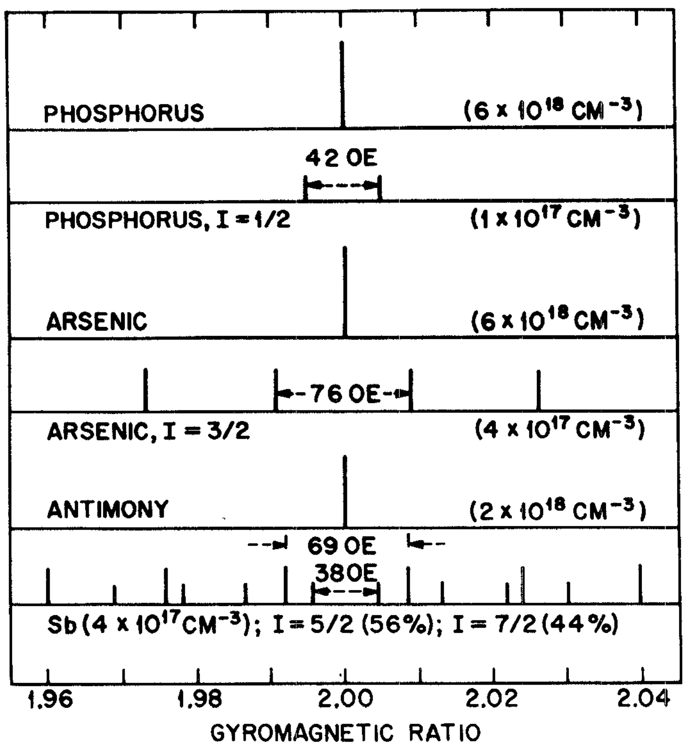

Fig. 15—A schematic representation of the absorption line spectrum for silicon doped with various amounts of phosphorous, arsenic, and antimony. Hyperfine structure is observed in samples with impurity content of the order of 10^{17} per cubic centimeter. (After Fletcher, Yager, Pearson, and Merritt.)

[81] A. M. Portis, A. F. Kip, C. Kittel, and W. H. Brattain, "Electron spin resonance in a silicon semiconductor," *Phys. Rev.*, vol. 90, p. 988; June, 1953.

[82] R. C. Fletcher, W. A. Yager, G. L. Pearson, and F. R. Merritt, "Hyperfine splitting in spin resonance of group *V* donors in silicon," *Phys. Rev.*, vol. 95, p. 844; August, 1954.

and Fletcher,[83] and sometimes even much longer, suggest possibilities for maser-type devices. The first contribution to the solid-state maser art was made last year by Townes and co-workers[84] in France using silicon. The original work on the maser at Bell Telephone Laboratories considered the use of a single crystal consisting of a silicon-29 isotope as a possible medium for such a device. With such narrow lines and long spin-lattice relaxation times, one can consider new possible devices using nonreciprocal or nonlinear properties of the spin resonance at low temperatures.

Conclusion

It is apparent that some of the recent developments indicate improvement and extension of present devices and the promise of new ones in the field of ferrites. The advent of the ferromagnetic garnet both in polycrystalline and single crystal form indicates the possibility of nonreciprocal ferrite components at lower microwave frequencies extending to the uhf region of the spectrum. The theoretical and experimental work on the nonlinear behavior of ferrites promises practical devices such as harmonic generators,[79] frequency mixers, and detectors.[85] Perhaps the most exciting possibility in this regard is the ferromagnetic resonance maser using ferrites or garnet crystals. However, whether it proves to be superior to existing devices at room temperatures or the paramagnetic maser[86] at low temperature remains to be demonstrated.

[83] G. Feher and R. C. Fletcher, "Relaxation effects in donor spin resonance experiments in silicon," *Bull. Amer. Phys. Soc.*, ser. II, vol. 1, p. 125; March, 1956.

[84] J. Combrisson, C. H. Townes, and A. Honig, "Utilisation de la resonance de spins," *Compt. Rend.*, vol. 242, p. 2421; May, 1956.

[85] D. Jaffe, J. C. Cacheris, and N. Karayianis, "Ferrite Microwave Detector," Diamond Ordnance Fuze Labs., Washington, D. C., Tech. Rep. No. TR-457; May, 1957.

[86] N. Bloembergen, "Proposal for a new type solid state maser," *Phys. Rev.*, vol. 104, p. 324; October, 1956.
H. E. D. Scovil, G. Feher, and H. Seidel, "Operation of a solid state maser," *Phys. Rev.*, vol. 105, p. 762; January, 1957.
A. L. McWhorter and J. W. Meyer, "A Solid State MASER Amplifier," presented at 15th Annual Conference on Electron Tube Research, Berkeley, Calif.; June 26, 1957.

Semiconductor microwave applications other than the existing detectors may be realized in the very near future in the form of junction rectifiers and transistors as a result of new developments. The use of the cyclotron resonance properties of holes and electrons in germanium promises practical applications for nonreciprocal devices in the millimeter wavelength region. The spin resonance in silicon and possibly other semiconductors may very well provide us with devices similar to the maser.

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