Ferrite Devices and Materials

J. Douglas Adam, *Fellow, IEEE*, Lionel E. Davis, *Life Fellow, IEEE*, Gerald F. Dionne, *Fellow, IEEE*, Ernst F. Schloemann, *Life Fellow, IEEE*, and Steven N. Stitzer, *Senior Member, IEEE*

Invited Paper

***Abstract*—The development and current status of microwave ferrite technology is reviewed in this paper. An introduction to the physics and fundamentals of key ferrite devices is provided, followed by a historical account of the development of ferrimagnetic spinel and garnet (YIG) materials. Key ferrite components, i.e., circulators and isolators, phase shifters, tunable filters, and nonlinear devices are also discussed separately.**

***Index Terms*—Ferrite circulators, ferrite isolators, ferrite materials, ferrite phase shifters, YIG filters, YIG limiters.**

I. Introduction

MICROWAVE ferrite devices permit the control of microwave propagation by a static or switchable dc magnetic field. The devices can be reciprocal or nonreciprocal, linear or nonlinear, and their development requires a knowledge of magnetic materials, electromagnetic theory, and microwave circuit theory. Unlike a magnetic metal, a ferrite is a magnetic dielectric that allows an electromagnetic wave to penetrate the ferrite, thereby permitting an interaction between the wave and magnetization within the ferrite. This interaction has been used to produce a variety of useful devices. There is an extensive ferrite literature and a brief list is given here [1]–[9], [175]–[177].

Spontaneous magnetism in electrically insulating iron oxides was observed in the 19th Century, but systematic research on ferrites did not occur until the 1930s. In 1949, Polder's theory [10] of the influence of ferrimagnetic resonance on magnetic permeability became a basis for understanding their microwave properties. Then, building on the idea of a "gyrator," a circuit element introduced by Tellegen [11], [178], Hogan at the Bell Telephone Laboratories (BTL), demonstrated microwave Faraday rotation in ferrites and used it to propose a new class of microwave components [12], [13]. This caused a surge of activity to investigate new types of devices and new materials to improve their performance. Over the last 50 years, many devices have been developed across the microwave spectrum for a wide range of power levels and are now commercially available. However, many challenges remain to be addressed if this body of knowledge is to be extended to meet demands for miniaturization, broader relative bandwidths, higher operating frequencies, and reduced costs.

The study of ferrite devices has advanced our knowledge of microwave circuit theory. Hogan [12] realized the first microwave gyrator. Using classical group theory and the scattering matrix theory developed in the 1940s, Carlin [14], [15] showed that a lossless symmetrical nonreciprocal three-port junction is a circulator, and this analysis was extended by Auld [16]. Weiss [17] used network theory to consider the synthesis of three-port circulators using nonreciprocal phase shifters and tee-junctions and showed that there are many solutions that require very little nonreciprocal phase shift. Bosma [18] and Davies and Cohen [19] used field theory to explore the conditions for perfect three-port circulation in stripline and waveguide circulators, respectively. Whether a ferrite device is reciprocal or nonreciprocal depends upon its symmetry, and Dmitryev [20] has classified ferrite devices in terms of their symmetry groups using concepts from crystallography.

The behavior of all microwave ferrite devices can be explained in terms of one or more of the following effects: *Faraday Rotation*—the rotation of the plane of polarization of a TEM wave as it propagates through a ferrite in the direction of the magnetization, *ferromagnetic resonance (fmr)*—the strong absorption that can occur when an elliptically polarized RF magnetic field is perpendicular to the direction of magnetization, *field displacement*—the displacement of the field distribution transverse to the direction of propagation resulting in more or less field in the ferrite region, *nonlinear effects*—at higher power levels amplification and frequency doubling are possible and subsidiary losses can occur, *spin waves*—short-wavelength waves of magnetization that can propagate at any angle with respect to the direction of magnetization. If the wavelength of such a wave is comparable to the dimensions of the ferrite sample, it is called a magnetostatic wave (MSW).

An understanding of the above effects requires a study of the interaction between the magnetization of the ferrite and the RF magnetic field. In the linear regime, this can be expressed in terms of the Polder tensor permeability [10], [21], [22], as described below.

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J. D. Adam is with Electronic Sensors and Systems, Northrop Grumman Corporation, Baltimore, MD 21203 USA.

L. E. Davis is with the Microwave Engineering Group, Department of Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology, Manchester M60 1QD, U.K.

G. F. Dionne is with Expert Services Personnel, MIT Lincoln Laboratory, Lexington, MA 02420 USA.

E. F. Schloemann is with the Consulting Scientist Division, Weston, MA 02493-1713 USA.

S. N. Stitzer is with the Northrop Grumman Corporation, Baltimore, MD 21203 USA.

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Permeability Tensor [μ] [10], [21], [22]

SI units are used in the following summary. However, much of the modern ferrite literature retains centimeter, gram, second (cgs) units for historical reasons. Therefore, conversion between the two systems is frequently necessary. A rigorous discussion of the relationships between various systems of units is given in [23] and [179].

The permeability tensor is derived from the tensor susceptibility (χ), which, in turn, is derived from the equation of motion of a magnetic dipole (due to electron spin) in the presence of both a static magnetic field (H_o) and a transverse RF magnetic field (H_x). This is shown in Fig. 1 and it is assumed that $|H_x| \ll |H_o|$.

Due to the electron spin, when a magnetic dipole ($\mathbf{m}$) is immersed in a static magnetic field, it precesses about the field axis with an angular frequency ω_o. The torque acting on $\mathbf{m}$ is given by $\mathbf{T} = \mu_o \mathbf{m} \times \mathbf{H}$, where μ_o is the permeability of vacuum. The spin momentum $\mathbf{J}$ is oppositely directed to $\mathbf{m}$, i.e., $\mathbf{m} = -\gamma \mathbf{J}$, where the gyromagnetic ratio $\gamma = 2.21 \times 10^5$ (rad/s)/(a/m). The torque acting on a body is equal to the rate of change of angular momentum of the body, i.e., $\mathbf{T} = d\mathbf{J}/dt$. Combining these equations, it follows that $d\mathbf{m}/dt = -\mu_o \gamma (\mathbf{m} \times \mathbf{H})$. If there are N unbalanced spins ($\mathbf{m}$) per unit volume, the magnetic dipole moment per unit volume (the magnetization) $\mathbf{M} = N\mathbf{m}$, and if all the magnetic moments precess in unison, the macroscopic form of the equation of motion can be written $d\mathbf{M}/dt = -\mu_o \gamma (\mathbf{M} \times \mathbf{H})$. If the dipole is subjected to a small transverse RF magnetic field H_x at an angular frequency ω, the precession will be forced at this frequency and an additional transverse component (H_z) will occur. Due to the time taken for $\mathbf{m}$ to precess, there is a phase difference of 90° between H_z and H_x. The susceptibility tensor relating $\mathbf{M}$ and $\mathbf{H}$ can be derived from this equation [21], [22] and the relative permeability tensor follows in a straightforward manner. The result is given in (1) below. The presence of "$\pm j$" in the off-diagonal terms is due to the 90° phase difference mentioned earlier and is the cause of nonreciprocal behavior.

$$[\mu_r] = \begin{bmatrix} \mu & 0 & j\kappa \\ 0 & 1 & 0 \\ -j\kappa & 0 & \mu \end{bmatrix} \tag{1}$$

where

$$\mu = 1 + \omega_o \omega_m / (\omega_o^2 - \omega^2) \tag{2}$$
$$\kappa = -\omega \omega_m / (\omega_o^2 - \omega^2) \tag{3}$$
$$\omega_o = \gamma \mu_o H_o \tag{4}$$
$$\omega_m = \gamma \mu_o M \tag{5}$$
$$\omega = 2\pi f. \tag{6}$$

$\mathbf{H_o}$ is the *internal* static magnetic-field intensity and it assumed here to be uniform. In practice, it will smaller than the applied field and nonuniform due to the nonelliptical shape of the sample [24], [25]. In the above description, the effects of losses have been neglected for clarity. If losses are present, μ and κ are complex quantities [21], [22], and if the transverse RF magnetic field is absent, the cone angle in Fig. 1 will decrease with time until $\mathbf{m}$ is aligned with $\mathbf{H_o}$. If the RF field is present, the precession will be maintained, but there will be some absorption of the signal. Just as with a gyroscope and the direction of gravity, there is a natural direction of precession that is associated with the direction of the static field, as shown in Fig. 1. If $\mathbf{H_o}$ is reversed, the precession is reversed. However, an interesting phenomenon occurs if the ferrite is immersed in a rotating elliptically polarized RF magnetic field that *drives* the precession. If the driven precession is against the natural direction, the cone angle θ is reduced. If they are in the same sense, the cone angle will increase. Furthermore, if they are in the same sense and the driving frequency is equal to the natural frequency, resonance will occur accompanied by strong absorption of the microwave signal. This loss mechanism is called fmr and it is used in resonance isolators. To take this absorption into account, a damping coefficient α is introduced into the equation of motion and the range of static magnetic field (at a fixed frequency) over which this absorption is significant is denoted by the linewidth ΔH. The relationship between α and ΔH is given by $\alpha = \mu_o \gamma \Delta / 2\omega$. In polycrystalline ferrites, random anisotropy field and residual porosity contribute to the linewidth, and the line shape is not Lorentzian due to spin-wave excitation. Other loss mechanisms in ferrites are associated with demagnetized and partially magnetized states [26]–[30] and are important in practice.

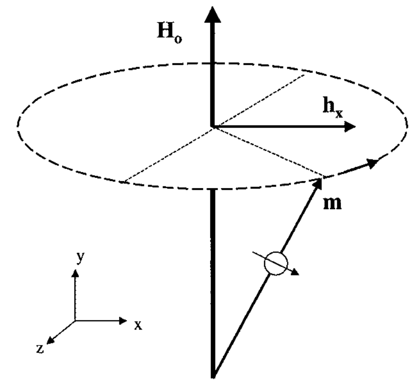

Fig. 1. Magnetic dipole moment $\mathbf{m}$ precessing about a static magnetic field $\mathbf{H_o}$.

Ferrite-Loaded Waveguides

There are three principal configurations for the study of TEM wave propagation in an infinite ferrite medium. These are when the direction of propagation is: 1) parallel with $\mathbf{H_o}$; 2) perpendicular to $\mathbf{H_o}$ and with the RF magnetic field *perpendicular* to $\mathbf{H_o}$; and 3) perpendicular to $\mathbf{H_o}$ and with the RF magnetic field *parallel* with $\mathbf{H_o}$. With the first configuration, the plane of polarization of a linearly polarized wave rotates as it propagates in the direction of the static field. This is known as Faraday rotation [1], [12], [13]. The wave can be decomposed into a right- and left-hand-side circularly polarized wave and the effective relative permeability for each wave is $\mu^+ = \mu - \kappa$ and $\mu^- = \mu + \kappa$, respectively. It follows that the two waves have different phase coefficients and, thus, from the reconstitution of the two constituent waves, it can be seen that the plane of polarization of the original wave is rotated. It is important to note that the rotation

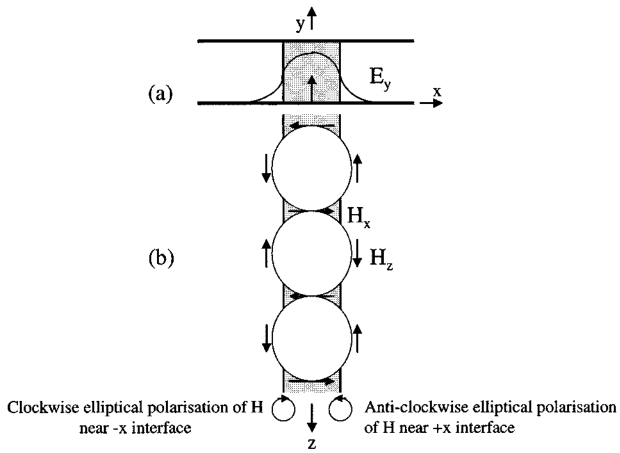

Fig. 2. Isotropic dielectric slab between parallel conducting plates supporting a TE mode propagating in the z-direction.

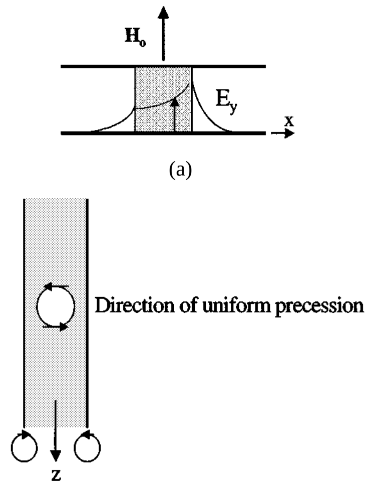

Fig. 3. Ferrite slab between parallel conducting planes with a TE mode propagating in the z-direction.

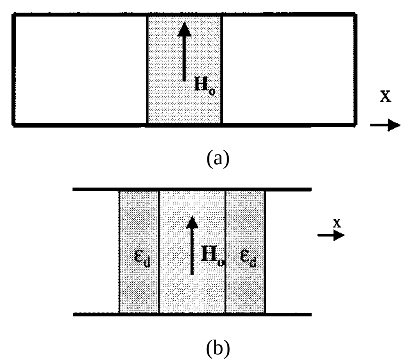

Fig. 4. Symmetrical reciprocal ferrite slab structures. (a) Rectangular waveguide. (b) Dielectric-loaded waveguide.

is nonreciprocal. That is to say, the plane of polarization of a linearly polarized wave propagating in the reverse direction rotates in the same direction as that of the forward wave, and reversal of the direction of propagation does not restore the original direction of polarization. This effect is used in Faraday rotation isolators and circulators. With the second configuration, the RF magnetic-field components are again perpendicular to the alignment of the magnetic dipoles, but the direction of propagation is perpendicular to the direction of magnetization. In this case, the effective relative permeability is given by $\mu_{\text{eff}} = (\mu^2 - \kappa^2)/\mu$. With the third configuration, the direction of propagation is perpendicular to the direction of magnetization, but the RF magnetic-field component is parallel with the static field. Therefore, at low power levels, there is no interaction with the magnetization. It is important to note that, from (2)–(6), μ^+, μ^-, and μ_{eff} are frequency dependent and that the phrase "device operation above (below) resonance" that appears in the literature should be interpreted carefully. For historical reasons, it usually means "operation with an internal static *field* above (below) that required for resonance," but sometimes it is used to mean "operation at a *frequency* above (below) that required for resonance."

Many modern ferrite devices use planar technology, but the essential principles of operation are more easily described qualitatively using rectangular structures as follows. We consider first a TE mode on a dielectric slab between two parallel perfectly conducting plates parallel to the zx-plane, as shown in Fig. 2, and then consider the perturbation of this behavior when the dielectric slab is replaced by a ferrite slab. The distributions of the $\mathbf{E}$- and $\mathbf{H}$-fields associated with the dielectric slab are shown in Fig. 2(a) and (b), respectively. With the TE_{10} mode, the electric field is perpendicular to the parallel plates, it is symmetrical about the plane of symmetry, and there is no field variation in the y-direction. The wave is guided because the dielectric/air interfaces provide reactive surface impedances and the field is evanescent outside the dielectric.

If the mode propagates in the z-direction, it can be seen that $\mathbf{H}$ is elliptically polarized in the clockwise direction in the x–z-plane near the $-x$ dielectric/air interface and elliptically polarized in the anticlockwise direction near the $+x$ dielectric/air interface.

Fig. 3 shows the dielectric slab replaced with a ferrite slab magnetized perpendicular to the parallel plates. When the wave propagates in the z-direction, the $\mathbf{H}$-field near the right-hand-side ferrite/dielectric interface is elliptically polarized in the same direction as that of the natural precession of the magnetization, whereas it is in the opposite direction near the left-hand-side interface. The effect of this difference in rotation direction is to produce a greater concentration of microwave field near the $(+x)$ interface and a reduced field near the $(-x)$ interface. This classical effect is known as transverse field displacement [1] and the resulting asymmetrical E field distribution is sketched in Fig. 3(a). If the direction of propagation is reversed, the senses of elliptical polarization are reversed and the field displacement will be toward the $-x$ interface. Although the surface reactances of the two ferrite/dielectric interfaces have been interchanged, the propagation constant is not affected, i.e., $\beta_+ = \beta_-$, and the structure is said to be reciprocal. This statement remains true if the structure is altered provided symmetry is maintained. Examples are shown in Fig. 4(a) and (b), in which external dielectric slabs or conducting planes parallel with the y–z-plane have been added. In the waveguide structure [see Fig. 4(a)], a TE_{m0} mode can be guided by the ferrite/dielectric interfaces or by the sidewalls [1]. In the first case, the field is evanescent outside the ferrite; in the second case, the field is harmonic between the sidewalls.

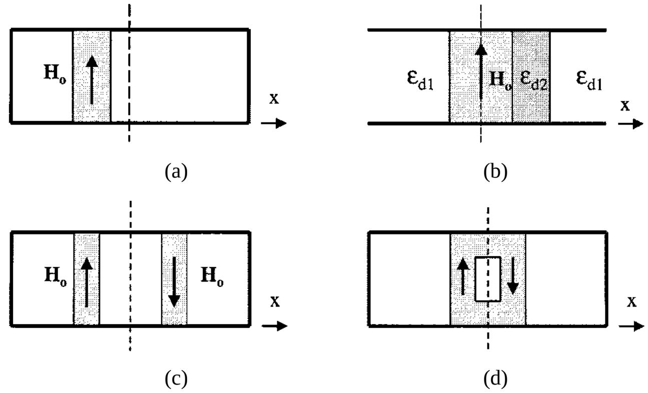

Fig. 5. Asymmetrical nonreciprocal ferrite slab structures. (a) Rectangular waveguide. (b) Dielectric-loaded ferrite waveguide. (c) Oppositely magnetized twin slabs in rectangular waveguide. (d) Ferrite toroid for latching.

This structure is used as a reciprocal phase shifter in which the phase shift is controlled by $\mathbf{H_o}$.

If some asymmetry is introduced into Fig. 4, e.g., by moving the ferrite off-center [see Fig. 5(a)] or removing a dielectric slab [see Fig. 5(b)], the ferrite interfaces no longer behave interchangeably when the propagation is reversed and the structure is nonreciprocal, i.e., $\beta_+ \neq \beta_-$.

A particularly important type of nonreciprocal asymmetry is the introduction of an oppositely magnetized ferrite slab [see Fig. 5(c)] [1]. With a high dielectric-constant material between the slabs, this structure has been developed into the toroid shown in Fig. 5(d). The application of this structure to phase shifters is discussed later in this paper.

The effects described above, and the canonical structures shown in Figs. 3–5, form the basis of resonance isolators, reciprocal and nonreciprocal phase shifters, and edge-mode isolators and circulators. For example, a resonance isolator can be designed by using a thin ferrite slab in the geometry shown in Fig. 5(a) and adjusting H_o to cause resonance absorption of the signal for one direction of propagation [1]. If the height of the slab is reduced to a fraction of the full height of the waveguide, and the slab width increased, the performance improves and the energy dissipated as heat in the ferrite can be extracted more efficiently via the waveguide walls. However, the complexity of the analysis is increased. The principles associated with Fig. 5(b) can be extended to the design of edge-mode isolators and circulators in microstrip [31]–[33], and the toroidal structure shown in Fig. 5(d) is used in nonreciprocal latching phase shifters, as discussed later in this paper.

Numerical Modeling

Mode matching [34], [35], Green's function [36]–[38] and finite-difference time-domain (FDTD) techniques [39], finite-element (FE) [40]–[42] and spectral-domain Methods [43]–[45], and equivalent-circuit methods [46], [47] are all used to simulate existing devices and to explore possibilities for new ones. Matching transformers and analytically inconvenient shapes of ferrite such as triangles can be included. Using the contour integration method [48]–[50], Macchiarella *et al.* [51] and Helszajn [52] have analyzed inhomogeneous stripline circulators with matching sections and triangular microstrip circulators with weakly magnetized regions, respectively. In early papers on circulators, it was assumed for simplicity that: 1) the ferrite/dielectric interface is a perfect magnetic wall except at the feeder points; 2) the disk is uniformly magnetized; and 3) losses could be neglected. These idealizations have now been removed. Nonideal boundary conditions and inhomogeneous magnetization in the ferrite disk in junction circulators have been modeled using annular structures and recursive Green's functions in two and three dimensions [37], [38]. Using the two-dimensional (2-D) approach [37], the frequency response of a circulator with quarter-wave matching transformers has been computed including the demagnetizing effects. The three-dimensional (3-D) analysis [38] enables horizontal inhomogeneities in the layer structure, and RF fringing fields above the microstrip surface to be taken into account in addition to the 2-D variations described above. An FDTD approach has been used [39] to model a stripline circulator including ferrite losses. Transformation from the time domain to the frequency domain yields the frequency response more quickly than the point-by-point process in FE methods. Other types of planar circulators have been proposed using ferrite coupled lines (FCLs) [53]–[56] and, as planar ferrite devices evolve, a better understanding of the complex modes on such structures will become important [43]–[45]. Progress has also been made in modeling hollow-waveguide components. A circular ferrite-filled waveguide with transverse four-pole static magnetic bias can be used as a differential phase-shift section [46], and its size can be reduced while maintaining phase accuracy by inserting sections of high-ε_r ceramic at intervals along the ferrite-rod waveguide [47]. "Hybrid" FE methods have been introduced to model a high-power phase shifter that avoid using approximate demagnetizing factors. A static field solver is used first to compute the nonuniform magnetization in the ferrite, and then this result is used in the computation of the eigenmodes of the ferrite waveguide with good agreement with experiment [40]. Full 3-D FE modeling has also been used to analyze transmission modes in latching ferrite phase shifters [41], [57]. Corner effects and the variation of the domains of magnetization were found to affect the phase shift significantly. An FE technique has also been developed to enable the effects of arbitrary, but uniform, directions of magnetization to be investigated in ferrite-loaded uniform inhomogeneous structures [42]. A mixed FE/analytic method has been used to solve the coupled microwave thermal problem in a full-height phase-shifter section [58]. In all aspects of ferrite device modeling, a key goal remains, i.e., to produce device models that circuit designers can use with commercial software packages in the same way that they can use libraries for active devices.

II. Ferrite Materials

Ferrites for microwave applications were first synthesized and studied during the 1940s by Snoek's group at the Philips Laboratories [59]. These pioneering achievements grew into comprehensive investigations of the spinel and hexagonal ferrite systems [60], and inspired research efforts of international scope. A concise, but inclusive, history covering that early period is found in the book by Lax and Button [1]. Reviews emphasizing various contexts followed as the evolution progressed [2], [61]–[65]. This brief summary focuses on the ferrite materials work that has directly enabled advances in microwave device technology over the past 50 years.

In the 1950s, the spinel families underwent intensive development. Prominent among these compounds were nickel (Ni) ferrite with zinc and aluminum magnetic dilutants and magnesium (Mg) ferrite with aluminum dilutant. The dielectric-loss properties of the Ni group were superior to the Mg group, but hysteresis loops lacked the squareness desired for latching devices because of magnetoelastic effects. The dielectric loss in Mg ferrite was reduced by Van Uitert at BTL [66] through the suppression of electron hopping by adding manganese (Mn) [67], thereby inspiring the creation of the useful MgMn family. The hysteresis loop problem of Ni ferrite was solved later by Mn additions, but for reasons related to magnetostriction [68].

In Grenoble, France, in 1956, Bertaut and his colleagues synthesized the rare-earth iron garnets and analyzed their magnetic characteristics [69]. These findings were quickly replicated and refined by Geller and Gilleo at BTL [70], and then expanded to form a base of crystallographic and magnetic data for most of the known garnet compounds, the most important of which was yttrium–iron garnet (YIG). By the end of the decade, both the spinel and garnet systems were becoming available to microwave device engineers.

During the 1950s and 1960s, when military needs for high-power phased-array radar with ferrite phase shifters were receiving great attention, magnetic loss caused by nonlinear spin-wave generation above an RF power threshold presented a challenging problem. Theoretical analyses of the phenomenon by Suhl at BTL [71] and Schloemann at the Raytheon Research Division [72] enabled device designers to avoid catastrophic losses by informed selection of the ferrite composition and operating conditions. Raising of the peak power thresholds could be accomplished by increasing average power losses through small concentrations of fast-relaxing ions. The broadening of ferrimagnetic resonance lines of polycrystals caused by magnetocrystalline anisotropy [73] and nonmagnetic inclusions, e.g., porosity [74], was also examined. Patton at Raytheon [28] and Vrehen at Philips [75] applied these concepts to define the "effective" linewidth of polycrystals for off-resonance conditions. The limits of intrinsic linewidths of single-crystal garnet were investigated at BTL [76]. Rado at the Naval Research Laboratory investigated microwave propagation in partially magnetized ferrites [77], and Green and Sandy at Raytheon later reported extensive characterizations of their microwave magnetic properties [26], [27].

Important advances in basic magnetic theory and properties relevant to ferrites were also achieved during these early years. The ferrimagnetic resonance relations for anisotropic single crystals were derived at BTL [78], the anisotropy of YIG as a function of temperature was measured at Harvard University [79], and comprehensive theoretical analyses of the anisotropy from multiple magnetic sublattices were carried out at Osaka [80] and Harvard universities [81]. These contributions influenced the development single-crystal garnet spheres at BTL [82] needed for magnetically tunable filters that were based on the narrow resonance lines.

By the 1970s, many of the important advances in bulk ceramic ferrites had taken place. However, for high-power waveguide phase shifters, two problems remained. As with the Ni spinels, the hysteresis loops of the garnets were too stress sensitive for latching operation, and the MgMn ferrites were too temperature sensitive for high power. Temme's group at the MIT Lincoln Laboratory (LL) found workable solutions through collaborations with industry: Trans-Tech reduced the stress sensitivity in the garnets by Mn substitutions [83], and Ampex implemented bismuth oxide as a sintering aid to densify the temperature-stable lithium (Li) spinel ferrite system [84]. Another program with Trans-Tech produced low-cost ferrite toroids for the waveguide phase shifters of the Aegis and Patriot radars [85].

During the decade, advances in the physics of ferrite properties continued despite a declining demand for microwave magnetic technology. Dionne at the MIT LL extended the multiple sublattice theory of ferrimagnetism to include magnetic dilution by correcting for spin-canting effects, and computer programs were created to predict the thermomagnetic characteristics of a wide range of rare-earth garnet [86] and the lithium spinel compositions [87]. The theory guided the development of new compounds, e.g., the calcium–vanadium–indium (CaVIn) low-linewidth ceramic garnets studied initially at Philips [88] and Raytheon [89], and also aided in the design of epitaxial garnet films for "bubble" memories and isolators for fiber-optical systems.

By the 1980s, conventional ferrites used in microwave devices had reached maturity. Garnets with their superior dielectric properties had found favor between L and X band; spinels with their higher magnetization capability could also find application up to Ka-band. Although the microwave losses of the hexaferrites have been too high for most practical devices, efficient 35-GHz self-biased circulators employing oriented M-type barium–strontium ferrite were demonstrated at the MIT LL [90].

During this decade, semiconductor transmit/receive (T/R) modules were replacing the waveguide ferrite phase shifters as the basic element for electronically steerable phased-array radars. As ferrite applications began to reach into the millimeter-wave bands where ferrites still had an advantage in power handling, the emphasis in bulk ferrites shifted to high-magnetization Ni and Li spinel diluted with zinc. In the standard microwave bands, microstrip and stripline circulators for integration with the T/R modules were emphasized. Film deposition of ferrites grew in importance as *miniaturization*, *hybrid structures*, and *monolithic circuits* were added to the ferrite lexicon.

Efforts in these directions continued through the 1990s, but seemed to result in more challenges identified than problems solved. As a partner in a Defense Advanced Research Projects Agency (DARPA)-sponsored industrial consortium, Westinghouse deposited microwave-quality polycrystalline ferrite on semiconductor substrates [91]. The main problems are thermal expansion mismatches between film and substrate and the need for post-deposition annealing to crystallize amorphous phases. The use of c-axis oriented M-type hexaferrites for millimeter-wave self-biased circulators has been hindered for similar reasons, but also because of the higher microwave loss

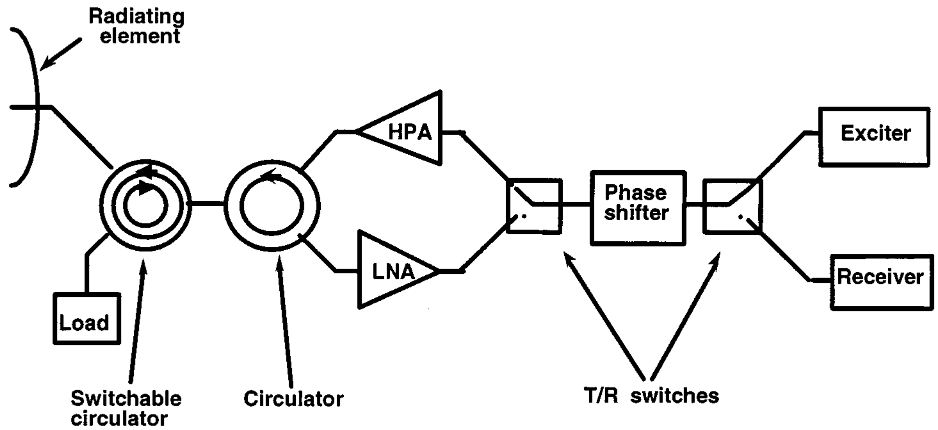

Fig. 6. Schematic diagram of phased-array antenna module.

[92] that may be fundamental to the electronic structure of the metal ions in the ferrite. Most recently, however, a team at Northeastern University reported the epitaxial deposition of hexaferrite thick films for phase-shifter applications [93].

At the MIT LL, ferrite requirements have been defined for cryogenic microstrip devices that exploit the low-conduction loss of superconductor circuits [94]. Los Alamos National Laboratory has reported deposition of epitaxial high-temperature superconductor films on ceramic garnet substrates using ion-beam-assisted deposition (IBAD) [95]. Among the materials issues remains the quest for single-crystal and epitaxial ferrite that meet microwave device requirements.

As this new century begins, the world of nanotechnology appears to offer little room for the micrometer dimensions of ferrite crystallites. Nonetheless, microwaves and the nonreciprocal propagation property of magnetized ferrite seem fundamentally linked for eternity. For the foreseeable future, it appears that the goals of ferrite materials development will remain, i.e., crystal perfection; chemical purity, homogeneity, and design accuracy; the continued development of low-cost film deposition processes for compatible precision interfacing with dissimilar materials; and the reduction of microwave loss.

III. Circulators and Isolators

A. Purpose and Function

In microwave systems that use a single antenna aperture for both sending and receiving, the function of circulators is primarily to facilitate the routing of outgoing and incoming signals to the transmitter or receiver as appropriate. This is illustrated in Fig. 6, which shows a schematic diagram of a phased-array antenna module using a switchable circulator in addition to an ordinary (nonswitchable) circulator. The module also contains two T/R switches. Their function can also be satisfied by two further circulators, but switches are generally preferred in these locations because of cost and size considerations. Circulators and isolators are made possible by the nonreciprocal character of the microwave behavior of ferrites (and certain other materials).

In microwave systems that use separate antenna apertures for sending and receiving, nonreciprocal devices are required in order to control the voltage standing-wave ratio (VSWR) seen by the high-power amplifier at the output of the transmitter, and also to control undesirable reflections from the receive antenna array. In this case, isolators rather than circulators are required. These isolators can be made by connecting a matched load to one of the ports of a circulator, but under some conditions, a "dedicated" isolator design may be preferable, as further discussed below.

The literature on microwave circulators and isolators is too extensive to be reviewed in detail in this short summary. For details, see the books devoted to this subject [1], [96]–[98], an excellent annotated bibliography [99], recent review papers [100], [101], and the other cited references.

B. Principles of Operation, Circulators

All circulators have at least three ports. The three-port circulator is the most frequently used type of circulator. The discussion in this paper, therefore, focuses on three-port circulators and, in particular, on "symmetric" three-port circulators (in which all three ports are equivalent). Other types of circulators are mentioned only briefly. The scattering matrix theory [102], [103] provides a convenient and general method of characterizing all circulators.

Detailed design theories for circulators have been developed primarily for rectangular waveguide, stripline, microstrip line, and image guide. Here, we focus on circulators in stripline or microstrip line because these devices are used most often in practice. Bosma's seminal work [36] established, for the first time, how a Green's function derived from Maxwell's equations could be used to predict circulator performance. The theory is based on the assumption of "magnetic-wall" boundary conditions at the edge of the metallization that defines the stripline or microstrip circulator. The magnetic-wall boundary conditions are very plausible for thin ferrite substrates (thickness $\ll$ junction disc radius), but are by no means rigorously valid, as emphasized by Latrach *et al.* [104]. If these boundary conditions are valid, the electromagnetic field in the circulator junction can be shown to consist of an E-field normal to the plane of the device (z-direction) and an H-field in the plane of the device (r- and ϕ-components). Bosma derived a Green's function $G(r, \phi;\ R, \phi')$, which relates the E-field at any point in the interior of the ferrite junction volume, to the azimuthal component $H_\phi(R, \phi')$ of the magnetic field existing at the boundary points (R, ϕ') of this junction volume. This relationship is

$$E_z(r, \phi) = \int_{-\pi}^{\pi} G(r, \phi;\, R, \phi') H_\phi(R, \phi')\, d\phi'. \qquad (7)$$

Wu and Rosenbaum [105] have extended Bosma's work significantly by showing how wide-band performance could be achieved by proper choice of relevant design parameters, such as the disc radius R and the coupling angle ψ.

In the theories of Bosma and Wu–Rosenbaum, the so-called effective permeability

$$\mu_e = (\mu^2 - \kappa^2)/\mu \qquad (8)$$

has an important role because its square root is a factor in the argument of the various Bessel functions that appear in the expression for the Green's function derived from Maxwell's equations. In Bosma's work [36], as well as that of Wu–Rosenbaum [105], it was implicitly assumed that μ_e is positive and real. A superficial inspection of the behavior of the Green's function in the limit $\mu_e \to 0$ may lead one to expect a significant singularity. There also exists a large amount of experimental data that appears to indicate that no usable circulator performance is possible when the frequency f is less than $f_H + f_M$, where $f_H = \mu_0 \gamma H$, $f_M = \mu_0 \gamma M_s$. (Note: the gyromagnetic ratio γ is here defined as $1/(2\pi)$, the value used in Section I.) This is the condition for $\mu_e < 0$, and it is also the frequency range, in which "low-field loss" is expected to prevent low-loss operation of circulators (and other devices) when the ferrite is not magnetized to saturation. It was, therefore, natural to disregard the possibility of circulator operation under the conditions in which $\mu_e < 0$.

However, Schloemann and Blight [106] showed that the Green's function actually has no significant singularity in the limit $\mu_e \to 0$. Furthermore, they demonstrated experimentally that low-loss circulator operation could be achieved for $\mu_e < 0$, provided that a high degree of bias-field homogeneity was maintained. In their experiments, they used a stripline configuration, with hemispherical ferrite pieces placed outside the ground planes of the circulator in order to simulate the homogeneous demagnetizing field of a sphere. Other, more practical, methods of realizing the high degree of bias-field homogeneity are available. In the experimental work reported by Schloemann–Blight [106], low-loss circulator operation was achieved for frequencies less than f_M, but the signal frequency could not be set below approximately $0.6 f_M$ without a significant increase in insertion loss. This result was unexpected at the time. The physical reason for it has only recently become clear, as discussed below.

C. Principles of Operation, Isolators

Isolators offer certain advantages over circulators in regard to size and cost. In applications that do not require the full range of circulator capabilities, a small low-cost isolator may be preferable over a circulator converted into an isolator by connecting a matched load to one of the ports.

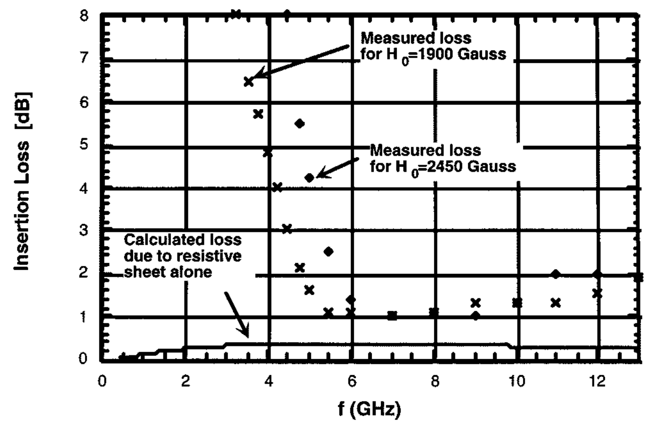

Fig. 7. Calculated and measured insertion loss of edge-mode isolator. Calculation neglects all losses other than that due to the resistive sheet, and assumes $H_{\text{int}} = 2$ Oe. Based on data from Hines publication [31].

Arguably the most promising type of isolator for broad-band applications is the "edge-mode" isolator (also known as "peripheral mode" isolator), which consists of a wide strip conductor on a ferrite substrate that is magnetized normal to its plane. A resistive sheet is disposed along one edge of the strip conductor. Operation of the device relies on the field displacement induced by the gyromagnetic properties of the magnetized ferrite. Since the strip conductor has to be very wide in order to produce the desired nonreciprocal attenuation, the characteristic impedance is low. Suitable impedance transformers are required when the device is connected to 50-Ω transmission lines.

Hines [31] has developed quantitative theory of the expected performance of this device. The results obtained from this analysis indicate that the device should have excellent broad-band performance if it is operated at a very low value of internal bias field. A high-frequency limit is imposed by the propagation of a higher order mode. The upper edge of the performance band of this device is limited to approximately $2f_M$ due to this effect. The theory suggests that no similar low-frequency limit exists, as long as the internal magnetic bias field is suitably low.

Hines's experiments [31] confirmed many aspects of his theory, but were at variance with the predicted low-frequency loss behavior, as illustrated in Fig. 7. He attributed the fact that the isolators became excessively lossy at low frequencies to the onset of "low-field loss," a well-known phenomenon in materials that are incompletely magnetized [107], [108]. This explanation is questionable, however, because the insertion loss was not reduced when the bias field was increased well beyond the value at which the magnetization would saturate.

D. Radiation Loss Due to Quasi-Static Interface Waves

The low-frequency loss observed in isolators and circulators can be explained by taking account of the excitation of quasi-static waves at the interfaces of the ferrite and dielectric materials [109]–[111]. This effect is widely known for devices in which the magnetic bias field is applied parallel to a strip conductor. Ganguly and Webb have developed a quantitative theory for this case and applied it successfully to magnetostatic surface-wave devices [112].

In the edge-mode isolator geometry, radiation loss due to excitation of quasi-static interface waves occurs at the side faces of the ferrite substrate, where the ferrite/dielectric interface is parallel to the bias field direction. A straightforward analysis [109]–[111] shows that these interfaces will support propagating quasi-static waves in the frequency range below $f_H + 0.5f_M$. Since the unexplained loss evident in Fig. 7 occurs at frequencies less than f_M, it appears that radiation loss alone cannot provide an adequate explanation. One must also take account of the fact that the measurements were made under conditions in which the bias field is strongly inhomogeneous.

In conventional bias magnets, the *external* magnetic field can be made very homogeneous, but the internal magnetic field in the ferrite substrates is necessarily inhomogeneous, especially near the edges of the ferrite substrates. This is due to the demagnetizing field, which is approximately equal to the saturation magnetization in the interior of the ferrite substrate (for thin substrates), but only one-half as large near the perimeter. For optimal performance, the external magnetic field has to be adjusted to a value at which the internal field in the interior is small, but positive to avoid low-field loss. The bias field near the substrate perimeter is then characterized by $f_H = 0.5f_M$. Hence, the onset frequency for low-frequency radiation loss is approximately equal to $f_H + 0.5f_M = f_M$ in this case. With careful design of the bias magnet, the internal magnetic field can be made substantially homogeneous (by placing high-permeability pole pieces close to the ferrite substrate). The onset frequency for low-frequency radiation loss is then reduced to $0.5f_M$.

E. Recent Developments

The Faraday effect (see Section I) is a fundamental property of ferrite materials that are magnetized parallel to the direction of propagation. This effect can be used to achieve circulator action in a quasi-optical geometry, which is especially useful for millimeter-wave applications. By combining a ferrite disc with suitable polarization filters, a four-port circulator has been demonstrated to have very low insertion loss and superior power-handling capability [113]–[116].

Circulators and isolators usually require a bias magnet to operate satisfactorily. However, some materials of the M-type hexaferrite family mentioned in Section II can be used without a bias magnet because these materials behave like permanent magnets themselves [117].

The integration of ferrite devices with integrated circuits based on semiconductor technology poses very challenging problems because the deposition of ferrite films generally requires much higher temperatures than can be tolerated by semiconductor substrates. Adam *et al.* [118] have described a process by which ferrite circulators can be integrated monolithically with monolithic microwave integrated circuits (MMICs) on GaAs substrates. In an alternative approach, single-crystal films of YIG, deposited on GGG substrates, can be bonded to silicon at 195 °C [119]. The GGG substrate is subsequently removed and a patterned metal circuit is generated at the YIG surface, resulting in an integrated circulator at X-band with a 1-GHz bandwidth.

In nonreciprocal devices based on ferrite films of relatively modest thickness, the ohmic loss due to the finite conductivity of the metal layers of the device become a significant or even dominating part of the total loss. Neidert and Philips [120], and How *et al.* [121]–[123] have described detailed analyses and supporting experimental data concerning this effect.

The size of stripline, microstrip, and waveguide circulators is generally comparable to the electromagnetic wavelength, and they are analyzed using field theory. By contrast, so-called lumped-element circulators can be very small compared to the electromagnetic wavelength, and they are analyzed using a circuit theory approach. Building on earlier work [124], [125], Miura *et al.* [126] have recently described an improved method of optimizing circulators based on the lumped-element design.

Dionne *et al.* [127] have investigated the integration of superconductive materials with ferrites in microwave devices and have demonstrated the feasibility of a switchable circulator based on this technology. The circulator most suitable for this application is the "ring network circulator," which is based on the same principles as the meander-line phase shifters discussed in Section IV [128], [129].

Although ferrites are most frequently used nonreciprocal material for circulators, other materials can also satisfy this function. Davis *et al.* [130], [131] have demonstrated the feasibility of circulators at millimeter-wavelengths, based on Y-junctions, where the junction area is filled with a semiconductor material that is exposed to a magnetic bias field. Other types of semiconductor circulators are based on the transistor effect and do not require a magnetic bias field. Tanaka *et al.* [132] originally proposed this type of circulator, and Ayasli [133] has further developed it. Carchon and Nauwelaers [134] have calculated the theoretical power and noise limitations of such circulators.

IV. Ferrite Phase Shifters

Ferrite phase shifters generally take advantage of the ability to control the permeability of a waveguiding medium to vary the phase velocity of a microwave signal passing through it. In most cases, the change in permeability changes the phase velocity and, therefore, the insertion phase. In a few cases, such as in the rotary field phase shifter, the orientation of the internal magnetization controls the phase shift.

A. Classification

Ferrite phase shifters can be classified in several different ways as follows.

- *Reciprocal versus nonreciprocal*: The phase shift in a reciprocal phase shifter is the same for signals propagating in either direction. It is different in the two directions in nonreciprocal types.
- *Driven versus latching*: Driven phase shifters require continuous control current. Latched types have a closed magnetic path and require only a momentary pulse of current to store a phase command.
- *Analog versus digital*: Analog types allow the insertion phase to be continuously varied by an external control current. Digital types generally comprise cascaded discrete

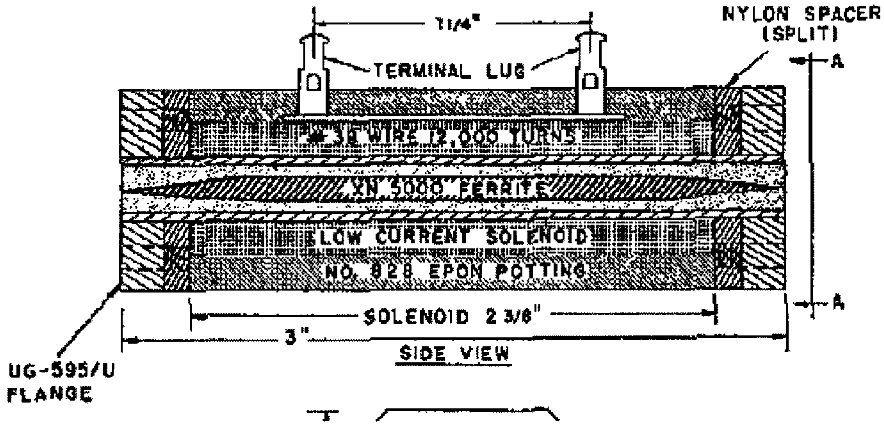

Fig. 8. Reggia–Spencer phase shifter (from [136]).

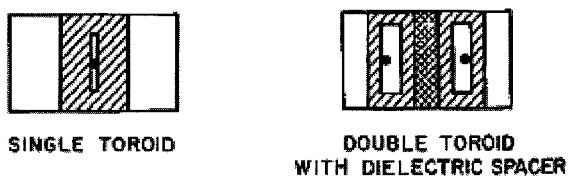

Fig. 9. Single and twin toroid phase shifters (from [141]).

phase shift sections that are switched between two specific insertion phase states, arranged in 180°, 90°, 45°, 22.5°, etc., steps. The phase resolution in the driven types is controlled by the resolution of the driver circuit. Resolution of the digital types is set by the number of discrete stages used.

B. Phase-Shifter Types

Reggia and Spencer [135] described one of the first practical ferrite phase shifters. It consists of a longitudinally magnetized ferrite rod in a waveguide. It is reciprocal, and the magnetizing solenoid, as shown in Fig. 8, must be driven continuously [136]. A latching version was described later [137].

Clavin investigated slabs mounted against the sidewalls of rectangular waveguide [138]. Another approach, using transversely magnetized ferrites, evolved into the twin-slab design. When the two slabs were joined by a magnetic path forming a closed toroid, as shown in Fig. 9, this device became latchable [139], [140]. Here, a magnetizing current was passed through a wire running down the center of the toroid. Early designs used discrete phase shift sections in 180°/90°/45° increments. Later devices used incremental adjustments of the remanent magnetization to produce different amounts of phase shift in a single device. Much greater phase shift is achieved by placing high dielectric-constant material between the slabs. A properly chosen dielectric slab draws the RF fields into the region around the two slabs. The twin toroid design has a dielectric slab between a pair of single toroids to serve the same purpose [141]. Two magnetizing wires are needed to thread the two toroids, but they avoid coupling to the strong RF fields in the center of the device.

The dual-mode phase shifter, shown in Fig. 10, follows a somewhat different path [142]. The main phase-shifting section is circular, and the RF propagates as a circularly polarized

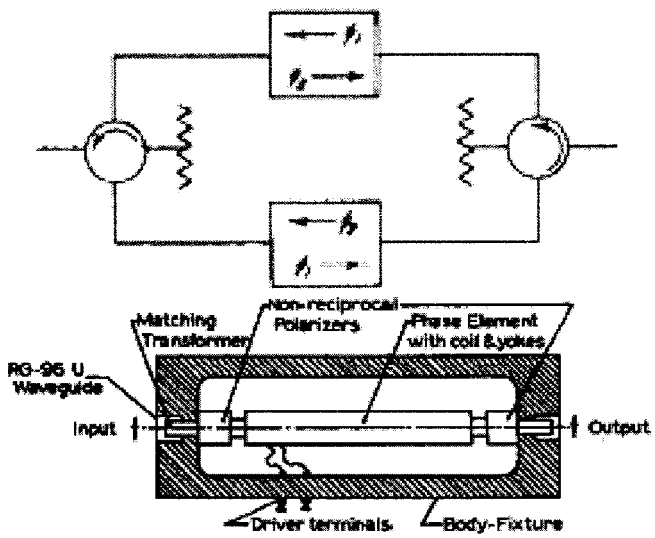

Fig. 10. Dual-mode phase shifter (from [142]). (a) Basic concept of dual-mode phaser. (b) Dual-mode phaser configuration.

wave through a longitudinally magnetized ferrite rod. Fixed permanent magnets applied to the ferrite sections at the ends of the device form nonreciprocal quarter-wave plates that convert a linearly polarized input wave to a circularly polarized wave. Phase shift is controlled by varying the current through a solenoid coil on the central phase-shifting section. This phase shift is inherently nonreciprocal, but since the end polarizers reverse the sense of circular polarization for the two propagation directions, the overall device is reciprocal.

The rotary field phase shifter in Fig. 11 has a similar appearance to the dual mode, but operates on a very different principle [143]. Again, nonreciprocal polarizers convert linear polarized RF into circular polarized waves. The phase-shifting section of ferrite is magnetized transversely by currents in a set of motor-like windings. The coil currents are adjusted to maintain in the ferrite a saturated region that can be rotated around the rod axis. This provides the electrical analog of the mechanically rotatable phase shifting section in a Fox phase shifter [144]. The insertion phase varies at twice the rotation angle of the saturated region, giving twice as much phase shift per unit length as the dual-mode type. The phase shift is in principle only a function of the rotation angle of the internal magnetic field. In addition,

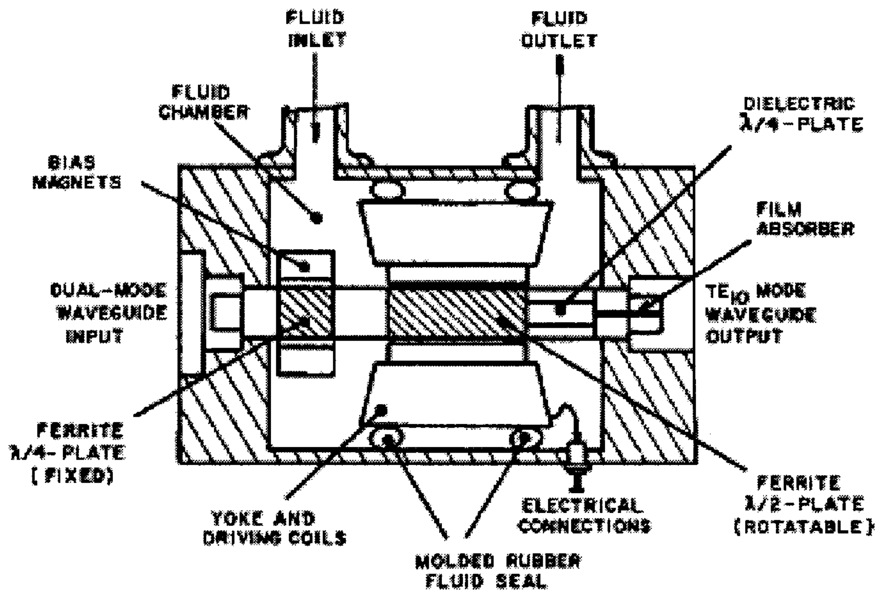

Fig. 11. Rotary field phase shifter (from [143]).

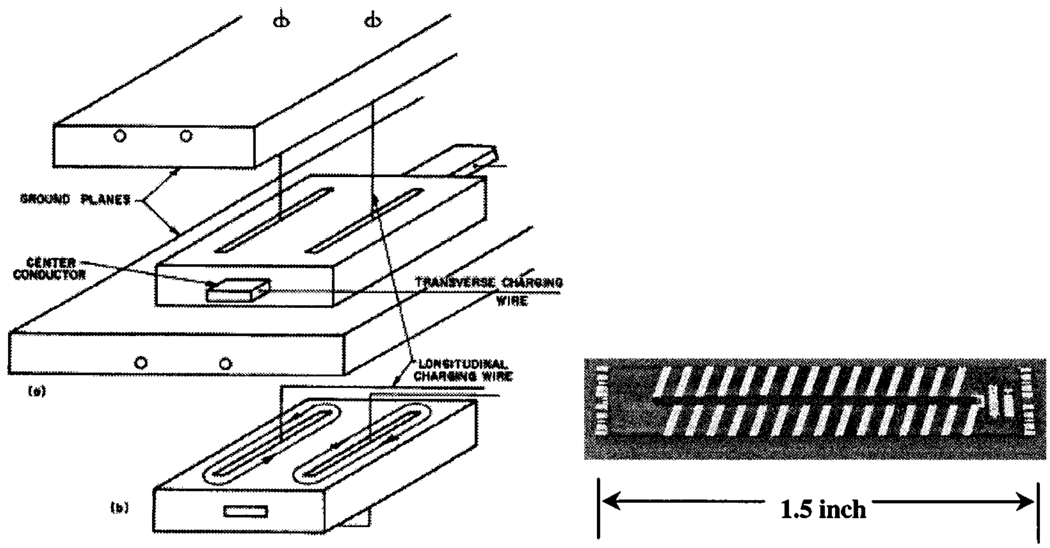

Fig. 12. TEM phase shifters. Machined ceramic (left-hand side) (from [145]), and LTCC (right-hand side), as described by Stitzer [57].

the ferrite is always saturated, resulting in more uniform insertion loss over all phase angles.

Various TEM phase shifters have been described. Simon *et al.* [145] described a ferrite-filled stripline device in which the dc magnetization was switched between a state transverse to the RF magnetic field and a longitudinal state (see Fig. 12). Individual phase bits were used. A more recent version [57] used low-temperature cofired ceramic (LTCC) techniques to minimize air gaps between the ferrite and the conductors, and integrated the coil windings with the structure. Continuous variation of the phase shift was achieved by incremental rotation of the internal remanent magnetization between the two extreme orientations.

A meander line can be used to enhance the phase shift by generating a circularly polarized RF magnetic field around the center conductor [146]. Other workers have investigated ferrite-filled TEM lines with continuously driven coils [147]. The higher insertion loss inherent in TEM devices has been significantly reduced by combining superconducting transmission lines with the meander-line approach [148], illustrated in Fig. 13.

C. Applications

The main use of ferrite phase shifters is in phased-array antenna systems. The direction of a beam radiated by an array of elements in a linear array can be steered by inserting a different phase shift in each radiator's feed. A phase control range of only 360° is required, but that full 360° range is required regardless of the scan angle.

The choice of phase shifter type is dictated by the following.

- *Frequency*: TEM devices are better suited to lower frequencies. Waveguides containing simple ferrite shapes such as rods are easier to fabricate with the high precision needed for the small sizes required at higher frequencies.

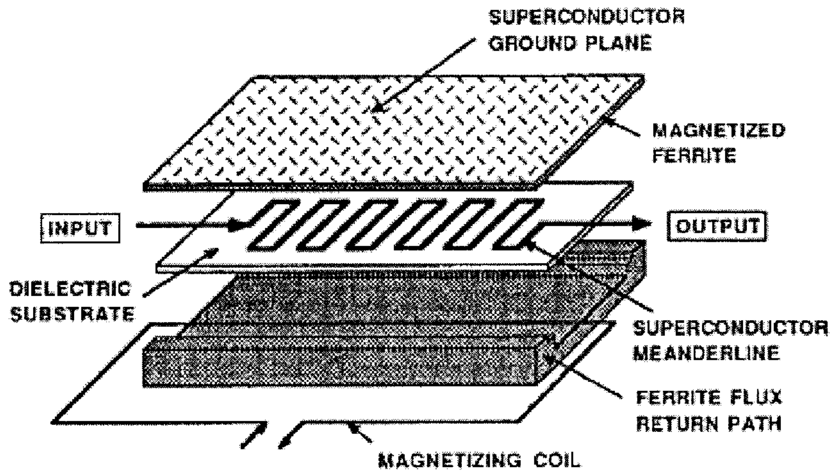

Fig. 13. Superconducting meander-line phase shifter.

- *Phase accuracy*: In some designs, the insertion phase varies significantly with frequency. In many types, the phase shift is a strong function of the remanent magnetization, which varies with temperature. The phase shift of a rotary field type is primarily a simple function of the angle of the magnetizing field, with little frequency dependence.
- *Switching time and energy*: If a nonreciprocal device is used in a radar application, the phase shifter must be switched between two different states between transmit and receive. Continuously driven phasers are generally very slow compared to latching types. If only one or a few phase shifters are required in a given system, the power consumed by a continuously driven phase shifter may be acceptable. In a phased-array antenna with hundreds or thousands of phase shifters, the choice is usually for a latched device.
- *Power handling*: Ferrite phase shifters can generally handle higher power than competing technologies. Designs in which the ferrite is in intimate contact with the housing will conduct heat dissipated in the ferrite away more readily, permitting higher average power handling. Peak power related nonlinear effects are discussed in Section VI.

V. YIG FILTERS

Microwave filters and oscillators that are electronically tunable over a decade in frequency rely on fmr in single crystals of YIG. YIG devices are widely used in test equipment, radar, and electronic-warfare (EW) systems and offer a wider electronic tuning range than other candidates including varactors, ferroelectrics, and microelectromechanical systems (MEMS). The narrow fmr linewidth of YIG, i.e., $\Delta H \leq 0.5$ Oe, yields potential resonator unloaded $Q = f/(\gamma \Delta H) > 5000$ at 10 GHz. The fmr resonance is tuned linearly by the magnetic field H so that $f = \gamma H$, where γ is the gyromagnetic ratio (2.8 MHz/Oe). A description of magnetically tunable microwave bandpass and band-stop filters using single-crystal YIG resonators was published in [149] and [150] respectively, and a comprehensive treatment of YIG resonators and filters was provided in [151].

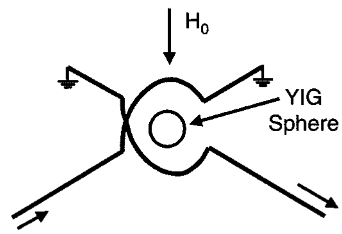

Fig. 14. Coupling structure for a single-stage YIG sphere filter.

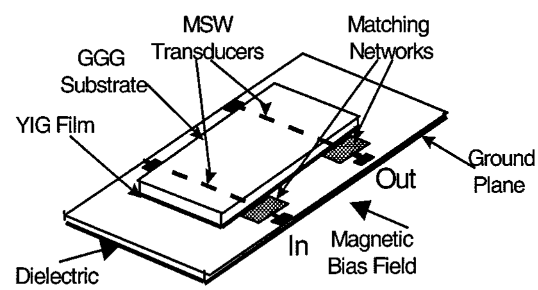

Fig. 15. Simple MSW device with microstrip transducers. Depending on design, this can provide time delay and filtering functions.

The coupling structure for a single-stage filter is shown in Fig. 14 and consists of two orthogonal coupling loops around a YIG sphere. The radius of the coupling loops controls the external Q of the resonator and minimum practical values are limited by the excitation of MSW resonances. Digitally controlled filters and oscillators tunable over multioctave or even decades of frequency are now available commercially. Recent developments have focused on size reduction, compatibility with packaging, and integration into higher level assemblies. Filters and oscillators with greater than octave tunability are commercially available in 1-in^3 packages and dissipate less than 5 W. The feasibility of further volume reduction was demonstrated in a three-stage notch filter that occupied 1 cm^3 and required less than <1 W to tune over the 7–9-GHz range [152]. This development investigated the use of permanent magnets to reduce electromagnetic power consumption, a concept that has also been applied to YIG tuned oscillators. The electromagnet power and saturation of the iron in the magnet poles determine the upper frequency for YIG tunable devices.

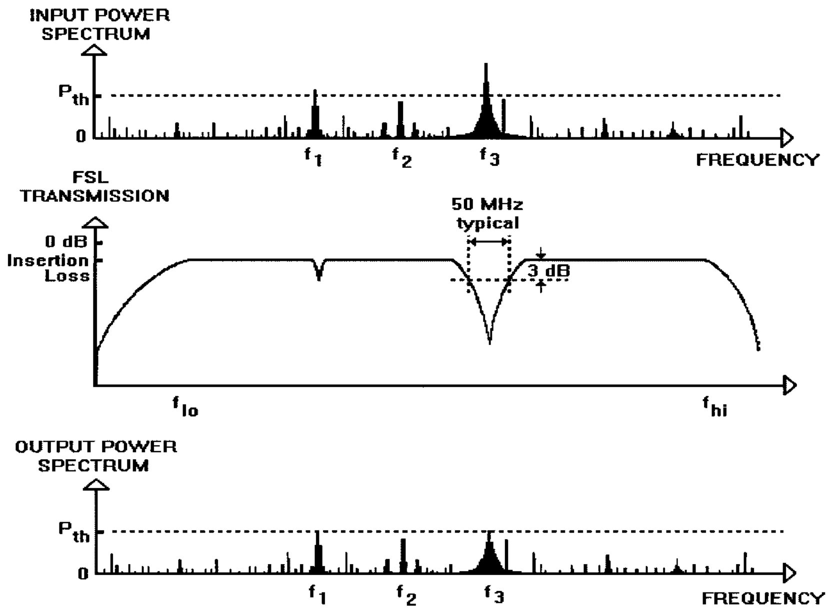

Fig. 16. Frequency response of an FSL, and input and output power spectra, from multiple weak and strong signals, showing the frequency selectivity inherent in YIG limiters.

Oscillators tunable over 33–50 GHz have been demonstrated [153]. M-type hexagonal ferrites have a large anisotropy field of $H_a \simeq 15$ kOe, and have been applied to tunable filters operating at 60 GHz and above [154], where a 50% reduction in magnet power was achieved.

The negative permeability shown by ferrite materials at frequencies higher than the fmr frequency enables wave propagation in structures with arbitrary small cross section over limited frequency ranges. These are referred to as MSWs since the electric-field contribution is negligibly small. Initial theoretical and experimental studies of MSW propagation in single-crystal YIG have been published [155], [156]. The theory was extended to planar epitaxial YIG films spaced from conducting ground planes in [157] and analysis of MSW transduction into YIG films was presented in [112]. Further experimental and theoretical developments are reviewed in several papers and books [158]–[160]. An example of a simple MSW device is shown in Fig. 15. Significant interest in MSW propagation in epitaxial YIG films arose because of the potential for analog signal processing at microwave frequencies similar to that performed by surface acoustic wave (SAW) devices at lower frequencies [161]. However, although the feasibility of many devices were demonstrated [162], none achieved the performance improvements necessary to replace incumbent SAW, YIG sphere, and rapidly developing digital approaches.

The potential for narrow-band tunable filters with very low loss has led to studies of high-temperature superconducting filters tuned by ferrites [163]. However, reductions in the ferrite loss at cryogenic temperatures are required for demonstration of practical devices.

VI. Nonlinear Magnetic Microwave Devices

EW systems are required to work in a high-signal density environment and receivers and signal processors are easily overloaded in this situation. An ordinary diode limiter placed in front of a wide-band receiver to limit the high-level signals, will attenuate all signals by the same amount. A frequency-selective limiter (FSL) is defined as one that can attenuate strong signals without attenuating other weaker signals present simultaneously (Fig. 16).

Most microwave FSLs utilize the frequency-selective nature of a magnetized ferrite. Above a critical RF magnetic-field level, the spin precession angle can increase no further, and coupling to higher order spin waves begins to grow exponentially. Energy is efficiently coupled to spin waves at approximately one-half the signal frequency and then into lattice vibrations (heat) in the ferrite. This mechanism has been analyzed [164] and characterized for the following three different modes.

1) "Premature decline" refers to the apparent drop in permeability when the precession angle saturates.
2) A "subsidiary resonance" can be induced, which produces an additional absorption band away from the normal fmr.
3) A "coincidence limiter" is one in which the fmr coincides with the subsidiary resonance.

The limiting threshold is generally highest in the subsidiary resonance type and is lowest in the coincidence type. An early review of ferrite power limiters has been given in [165].

The threshold power ranges from tenths of milliwatts for YIG spheres in coincidence limiters [166] to tens of watts for polycrystalline ferrite in subsidiary resonance devices [167]. In any mode, the critical field strength is proportional to the spinwave linewidth ΔH_k of the ferrite. YIG has the narrowest known linewidth, on the order of 0.2 Oe for single crystals. The effective value of ΔH_k for polycrystalline ceramic ferrites is typically in the tens of oersteds. These are used in high-power receiver protectors [168] to prevent burnout.

Ferrite FSLs have been realized in a variety of transmission-line structures. Threshold power usually has to be traded off for bandwidth [169]. Nonresonant stripline formed directly on single-crystal YIG films can operate over octave bandwidths [170]. The below-threshold insertion loss in these devices is controlled by the normal conduction loss of the transmission line and dielectric losses in the ferrite, which is usually very small. Another type of FSL is based on the nonlinear excitation of spin waves in structures that can propagate MSWs. These devices have limiting thresholds as low as -30 dBm [171].

A related nonlinear device is the signal-to-noise enhancer (SNE). It performs the opposite function to the FSL. At low-signal levels, the SNE absorbs most of the signal energy. At high-signal levels, the absorption mechanism saturates, allowing a larger fraction of the signal to pass. As in the FSL, this effect is frequency selective, meaning that the SNE can attenuate low-level signals such as broad-band noise, while allowing strong coherent signals to pass with relatively little attenuation. The SNE utilizes MSW in a thin-film structure [172] and was developed for use in frequency memory loops. Commercial applications of the SNE concept include improved detection sensitivity in DBS TV receivers [173].

The FSL and the SNE depend on the amplitude of the magnetic precession being driven to a saturation level. It takes time for the precession amplitude to grow to this level, thus, the limiting action does not take place instantaneously. The result is a characteristic spike leakage, where the leading edge of a pulsed signal is essentially unattenuated. Since the limiting behavior depends on the recent history of the spin waves, the duration of the spike can be reduced by priming the spins with a sample of the RF signal ahead of time [174].

VII. Conclusions

Ferrite devices have played a key role in most microwave systems and will continue to do so as they provide unique nonreciprocal and frequency-selective properties. The development and understanding of ferrite materials was one of the successes of solid-state physics and chemistry in the 20th Century and continuing research is required to provide self-biasing materials in the millimeter-wave and microwave range and materials with significantly higher saturation magnetization than 5000 G. Larger quantities of compact high-performance circulators will be required as active aperture radar and multifunction systems become more ubiquitous on defense platforms. YIG filters will continue to play a key role in test and electronic warfare equipment and, if size and cost can be reduced, they may impact the commercial wireless market. Usage of ferrite phase shifters will continue to decline, except for low-cost electrically steered antenna systems. Frequency-selective nonlinear devices have the potential to solve receiver dynamic range and interference problems, but a significant application is required. In all cases, reductions in size and cost and increased integration will continue to be required.

Acknowledgment

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J. Douglas Adam (M'77–SM'89–F'91) received the B.Sc. degree in electrical engineering from the University of Strathclyde, Strathclyde, Scotland, the M.Sc. and Ph.D. degrees in electrical engineering from the University of Glasgow, Glasgow, Scotland.

Since joining the Northrop Grumman Corporation in 1977, he has developed novel signal-processing devices based on microwave interactions with epitaxial YIG films, including MSW channelizers, FSLs, and monolithically integrated circulators on semiconductor substrates. He has had management responsibility for research and development of miniature filters, MEMS devices, miniature time standards, ceramic packaging, and crystal growth. He is currently Manager, Advanced Materials and Electronic Device Research, Northrop Grumman Corporation. He has authored or co-authored over 70 publication. He holds 16 patents.

Lionel E. Davis (SM'64–LF'95) received the B.Sc. (eng) degree from the University of Nottingham, Nottingham, U.K., and the Ph.D. and D.Sc. (eng) degrees from University College London, London, U.K.

From 1959 to 1964, he was with Mullard Research Laboratories, Redhill, U.K. From 1964 to 1972, he was a faculty member in the Electrical Engineering Department, Rice University, Houston, TX. From 1972 to 1987, he was with Paisley College, Paisley, Scotland, where he was Professor and Head of the Department of Electrical and Electronic Engineering. In 1987, he joined the Department of Electrical Engineering and Electronics, University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., where he is currently Professor of communication engineering and Head of the Microwave Engineering Group. He has been a Visiting Professor at University College London and the University of California at San Diego, and has been a consultant for several companies. He has carried out research on passive components, high-T_c superconductors, dielectric-resonator antennas, chiral materials, and liquid crystal films. His current research interests are in gyrotropic media and nonreciprocal components for microwave, millimeter-wave, and optical wavelengths.

Dr. Davis is a Fellow of the Institution of Electrical Engineers (IEE), U.K., and of the Institute of Physics. He is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS) Technical Programme Committee and co-chairman of the IEEE MTT-S Committee on Microwave Ferrites. Until recently, he was a member of the Administrative Committee of the UKRI MTT/AP/ED/LEOS chapter, and he initiated the Houston chapter of the IEEE MTT-S. He served on the Council, the Microwave Theory and Devices Committee, and the Accreditation Committee of the IEE and is member of the Peer Review College of the U.K. Engineering and Physical Sciences Research Council (EPSRC).

Gerald F. Dionne (SM'71–F'94) received the B.Sc. degree in physics from the University of Montreal (Loyola College), Montreal, QC, Canada, the B.Eng. degree in engineering physics from McGill University, Montreal, QC, Canada, the M.S. degree in physics from Carnegie-Mellon University, Pittsburgh, PA, and the Ph.D. degree in physics from McGill University, Montreal, QC, Canada.

He served as a member of the physics faculty at McGill University, was also involved with semiconductor device development with both IBM and the Sylvania Division of GTE (now Verizon), and investigated electron emission and cesium vapor ionization for thermionic energy at Pratt and Whitney Aircraft. Since 1966, he has carried out research at the MIT Lincoln Laboratory, Lexington, MA. His numerous publications include original contributions in fields of magnetism theory and the properties of ferrimagnetic materials for microwave, millimeter-wave, and magnetooptical applications, the physics of electron emission, and the development and application of millimeter- and submillimeter-wave radiometry. From his studies of the role of large polarons in high-T_c superconductivity, he has constructed an effective model for giant magnetoresistance effects in magnetic oxides. He holds patents on microwave ferrite, magnetostrictive, and superconductor devices.

Dr. Dionne is a member of the American Physical Society and the Society of Sigma Xi.

Ernst F. Schloemann (SM'71–F'78–LF'99) received the M.S. and Ph.D. degrees from the University of Goettingen, Germany, in 1953 and 1954, respectively, both in theoretical physics.

From 1954 to 1955, he performed post-doctoral research in theoretical solid-state physics at the Massachusetts Institute of Technology. In 1955, he joined the Raytheon Research Division. During the 1961–1962 academic year, he served as a Visiting Associate Professor at the W. W. Hansen Microwave Laboratory, Stanford University. In April 1964, he became a Consulting Scientist in special recognition of his research achievements. In 1966, he was a Visiting Professor at the University of Hamburg, Hamburg, Germany. He has made numerous important contributions to the theory of resonance linewidth in polycrystalline magnetic materials and to the theory of fmr at high signal levels. In the 1970s, he developed a novel technique for the recovery of aluminum and other nonferrous metals from solid waste. He retired from Raytheon in 1995, and is now an independent consultant. He has authored or co-authored research papers on the thermal conductivity of dielectric solids, magnetostatic and magnetoelastic waves, domain-wall dynamics, computer memories, YIG filters, low-noise YIG-tuned oscillators, broad-band circulators, miniature circulators, broad-band isolators, and RADAR cross-sectional reduction. He has also authored or co-authored over 130 scientific papers. He holds 21 U.S. patents and several foreign patents. From 1974 to 1976, he was a member of the Editorial Board of the *Journal of Applied Physics* and *Applied Physics Letters*.

Dr. Schloemann is also Fellow of the American Physical Society. He is a member of the IEEE Magnetics Society, the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), and Sigma Xi. From 1970 to 1973, he was a member of the Editorial Board for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was the recipient of the 1990 Raytheon Thomas L. Phillips Award for Excellence in Technology. He was also the recipient of a Fulbright Scholarship.

Steven N. Stitzer (M'74–SM'91) received the B.S.E.E., M.S.E.E., and Ph.D.E.E. degrees from Carnegie-Mellon University, Pittsburgh, PA, in 1970, 1971, and 1974, respectively.

In 1974, he joined the Westinghouse Electronic Systems Group (now Northrop Grumman Electronic Systems), Baltimore, MD, where he has been involved primarily with the design, development, production, and automated testing of high-power microwave control devices. These include gas plasma and diode receiver protectors, and high-power p-i-n diode switches and attenuators. Most of his recent work has involved modeling, analysis, and design of ferrite phase shifters, circulators, isolators, frequency-selective power limiters, and ferroelectric phase shifters. He is an inventor or co-inventor on 15 patents in these areas. He has authored, co-authored, or presented over 20 papers on these topics.

Dr. Stitzer served as an officer in the Baltimore IEEE Microwave Theory and Techniques Society (IEEE MTT-S) chapter and was chairman from 1980 to 1981. He was chairman of the IEEE MTT-S Standards Subcommittee P457 from 1980 to 1982. He served as Publicity Chairman on the 1986 IEEE MTT-S International Microwave Symposium Steering Committee, and was overall Steering Committee Chairman for the 1998 IEEE MTT-S International Microwave Symposium (IMS), Baltimore, MD. He has served on the IEEE MTT-S IMS Technical Program Committee since 1993. He is a member of the IEEE MTT-13 Microwave Ferrites Technical Committee. He is currently chairman of the IEEE MTT-S Historical Collection Committee. He is a member of the Board of Directors of the Historical Electronics Museum, Linthicum, MD. He was a recipient of the 2000 IEEE Millennium Medal.