Microwave Ferrite Devices: The First Ten Years

KENNETH J. BUTTON, FELLOW, IEEE

I. Introduction

THE first twenty years of microwave radar development was done entirely without the benefit of ferrite devices. The first experimental microwave ferrite device was demonstrated in 1949. Ten more years of research and development on the devices was required before significant performance was achieved and large scale commercial participation began. This is the story of those ten years.

A. Early History

The decades of delay in the use of ferrite devices in microwave systems was not caused by any lack of information or scientific understanding of the ferrite materials themselves. Reliable, quantitative studies have been made since 1910 with the expectation that their high electrical resistivity might be useful in reducing the eddy-current losses in inductors and transformers. A large variety of synthetic ferrites were prepared by Hilpert in 1909 with this objective in mind.

B. Development and Measurements of Synthetic Ferrites

The most extensive work carried on between 1933 and the end of World War II took place at the Philips Research Laboratories in Eindhoven, The Netherlands, where the development of ferrite materials was first brought to the stage of commercial significance. These contributions were made principally by Snoek, Verwey, and their coworkers. Snoek [1]–[3] began a systematic investigation of the artificial ferrite materials in an effort to discover the influence of preparation techniques and composition on the loss and magnetic properties. He wished to prepare ferrites having low hysteresis, high resistivity, and high permeability which could be used at frequencies up to the megacycle range.

C. Néel Model of Ferrimagnetism

After the war, a great deal of activity in the field of fundamental investigations was renewed. Verwey and Heilman [4] and Verwey, De Boer, and Van Santen [5] continued their X-ray studies of the lattice constants of a number of oxides having the spinel structure and concluded that Mn, Fe, Co, Mg, Cu, and Ni ferrites, which were magnetic, had an inverted structure and Zn and Cd ferrites which were not ferromagnetic, had a normal spinel structure.

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The author is with the Massachusetts Institute of Technology, National Magnet Laboratory (NML), Cambridge, MA 02139. NML is supported by the National Science Foundation.

In order to explain experimental findings of this kind, Néel [6] announced his celebrated theoretical contribution which dealt with the basic phenomenon of spin–spin interaction taking place in ferrites and antiferromagnetic materials. He postulated the exchange interaction similar to that in ferromagnetic metals except that he suggested the possibility of spins aligning in the antiparallel sense. Applying the molecular-field theory to the ferrites, he introduced the concept of magnetic sublattices. He developed theoretical curves describing the behavior of the magnetic susceptibility as a function of temperature by considering several different types of interactions among the spins. A more detailed examination of the basic interactions of the spin system was made by Anderson [7] and Van Vleck [8], [9], who developed the theory of superexchange for these materials by using some of the basic principles proposed by Kramers [10]. Superexchange interaction leads to an antiferromagnetic alignment of spins.

II. Microwave Applications and Related Theory

The microwave applications of ferrites had their foundation in the early work on the Faraday effect.

A. The Farady Effect

The first device using the Faraday effect in ferrites was built by Luhrs and Tull [11], who developed a microwave switch.

The theory of applications of the Faraday rotation to ferrites is very similar to that used for explaining the behavior of the Faraday rotation in optical media. In deriving the tensor nature of ferromagnetic materials at microwave frequencies, Polder [12], [13] used the same phenomenological approach. He derived expressions for the propagation constant or index of refraction analogous to the Appleton–Hartree [14] equation for magnetoionic media. Subsequently, Roberts [15] observed the Faraday rotation in ferrites and found it to be in accordance with Polder's theory. A similar measurement was made in circular waveguide by Goldstein, Lampert, and Heney [16] for the magnetoionic medium.

Luhrs [17] also discussed the application of the Faraday and Kerr magnetooptical effects in transmission lines. Perhaps the most significant contribution was made by Hogan [18], [19] who utilized Faraday rotation in the development of his microwave gyrator, which was the equivalent of Tellegen's (20) nonreciprocal network. In addition, Hogan outlined the use of the gyrator for one-way transmission lines, circulators, switches, variable attenuators, and modu-

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lators. He extended the theoretical work of Polder for the infinite medium and correlated his experimental results with the theory.

1) The Faraday Rotator:

Hogan's work stimulated a great deal of activity in the investigation of the ferrite Faraday rotation for the development of microwave devices. Some further experimental work on the gyrator was carried on by Smullin [21]. Sakiotis and Chait [22] investigated the Faraday rotation in circular waveguides for a number of ferrites and measured both rotation and loss. Some new applications of the Faraday rotator were made by Allen [23], who constructed a microwave magnetometer for measuring magnetic fields, and by Olin [24] who used a Faraday rotator as an amplitude modulator for controlling a microwave sweep oscillator. The most extensive treatment of the microwave application of ferrites up to this point was given by Rowen [25]. He discussed the techniques of broadbanding, minimizing losses, and optimizing isolation in nonreciprocal components.

2) Exact Theoretical Solutions:

Following the theoretical work of Polder [13] and Hogan [18], [19] on the propagation and Faraday rotation in the infinite medium, a number of workers began to analyze the problem of propagation in bounded ferrite media. The problem of Faraday rotation in circular guide completely filled with ferrite was treated by Suhl and Walker [26].

Suhl and Walker [27], in their treatise on "Topics in Guided-Wave Propagation through Gyromagnetic Media," discussed in great detail the problem of the completely filled cylindrical guide containing media with both dielectric and permeability tensors characteristic of gyromagnetic media.

3) Perturbation-theory Approximation:

The exact solution does not ordinarily provide an explicit expression for the propagation constant in a waveguide containing a ferrite. An approximate treatment is often sufficient, and the results are much more useful from the analytical point of view. Lax and Berk [28] had solved the ferrite-loaded-cavity problem by using the first-order perturbation-theory approximation, and Lax [29] extended the method to the waveguide problem.

Heller and Lax [30] applied first-order perturbation theory to solving the nonreciprocal propagation constant of a circular guide operating in a TE_{10} mode and containing a circumferentially magnetized ferrite cylinder. Heller [31] obtained a perturbation solution for the nonreciprocal ferrite attenuator in rectangular waveguide and derived an expression for the optimum location of the ferrite rod. His treatment was modified by Lax [32], who also considered the nonreciprocal loss in a Faraday-rotation resonance isolator. Using the first-order perturbation theory, Lax [32], [33] obtained expressions for the figure of merit for the Faraday rotator and the nonreciprocal phase shifter in rectangular guide, as well as for the resonance isolator.

B. Rectangular-Waveguide Components

The load isolators, nonreciprocal phase shifters, and ferrite circulators have proved to be more practical than the Faraday-rotation devices, particularly when designed for operation at low microwave frequencies or under conditions of high RF power.

1) Nonreciprocal Phase Shifter:

The initial observations of nonreciprocal effects in rectangular waveguide were made by Sakiotis and Chait [22]. Then Kales, Chait, and Sakiotis [34] clearly showed the nonreciprocal nature of both the phase shift and attenuation in rectangular waveguide containing transversely magnetized ferrite slabs. Rowen [25] reported a set of measurements of the phase shift and differential phase shift in a rectangular waveguide as a function of the position of a transversely magnetized ferrite slab. He also compared a circulator incorporating this component to a Farady-rotation circulator. Lax, Button, and Roth [35] obtained a quantitative solution for the nonreciprocal ferrite phase shifter consisting of either one or two transversely magnetized ferrite slabs in a rectangular waveguide. The solution was worked out for variable applied magnetic field, ferrite-slab thickness, and slab location. The nonreciprocal distortions of the RF field patterns were plotted for the fundamental TE mode.

Kales [36] gave a critical discussion of the nonreciprocal properties of ferrites in a rectangular waveguide. A more complete examination of the behavior of ferrite slabs in rectangular waveguide, along with some experimental data, was presented by Fox, Miller, and Weiss [37]. They supplied the first detailed exposition of the use of the nonreciprocal phase shifter for application in circulators.

2) Resonance Isolator:

The observations of Sakiotis and Chait [22] of the nonreciprocal loss in a ferrite-loaded rectangular waveguide led Kales, Chait, and Sakiotis [34] to suggest its use as a resonance isolator. Such a device, consisting of a vertical slab in rectangular waveguide, was described by Rowen [25], with a reverse-to-forward ratio of attenuation (in decibels) of about 30. Experimental measurements of the resonance isolator in both circular and rectangular waveguide were presented by Chait [38], who obtained larger reverse-to-forward ratios. Kales [36] discussed the properties of the resonance isolator in terms of the internal fields and showed curves of reverse-to-forward ratio as high as 70 with a ferrite rod used as an absorption element. The most detailed treatment of the experimental properties of the resonance isolator using a vertical slab was given by Fox, Miller, and Weiss [37]. They showed experimental curves of the resonance loss for different positions of the ferrite in the waveguide. A most important principle was demonstrated and the highest performance was achieved by Weiss [39] through the use of dielectrics placed adjacent to the ferrite absorbing element.

3) The Field-Displacement Isolator:

The exact theoretical solution of the nonreciprocal phase shifter by Lax, Button, and Roth [35] had shown that the RF field patterns of the distorted TE_{01} mode were different for opposite directions of propagation. Fox, Miller, and Weiss [37] visualized a point in the waveguide where the transverse RF electric intensity would be small for one direction of propagation and large for the reverse direction.

They placed a resistance card at this point and demonstrated nonreciprocal attenuation. This resistance sheet isolator consisted of a thick, transversely magnetized ferrite slab against the sidewall of the guide and a resistance sheet attached to the broad face of the slab. They also developed both a three- and four-port circulator depending on the same phenomenon. Sullivan and LeCraw [40] showed experimentally that the best performance of the resistance sheet isolator is achieved only if the ferrite slab is displaced slightly (less than 1 mm) from the sidewall of the waveguide. Fox [14] also announced that this latter version was superior to his original isolator. The properties of the field-displacement isolator at 55 GHz were investigated by Turner [42], who obtained reverse-to-forward ratios of attenuation of 100 over a 2-GHz band. Weisbaum and Boyet [43] described the design of the field-displacement isolator using a ferrite slab and resistance sheet near each side of the waveguide. A comprehensive experimental treatment and theoretical discussion of the field-displacement isolator were given by Weisbaum and Seidel [44]. Button [45] extended the theory to develop criteria for the optimum design. Another device which makes use of the differential field-displacement properties of the two contrarotating components of the TE_{11} mode in a ferrite-loaded circular waveguide was developed by Vartanian, Melchor, and Ayres [46].

4) Three-Port Circulator:

The possibility of a three-port circulator was postulated by Carlin [47] on theoretical grounds from the scattering-matrix treatment of the three-port microwave junction. The present form of the *Y* circulator was first described by Schaug-Pettersen (48), and the analysis of the three-port junction containing a symmetrically disposed ferrite was given by Fowler [49].

Although the theory of operation of the three-port circulator had not been formulated in terms of the local boundary-value solution, Heller [50] had stated the general theorem involving the nonreciprocal scattering of electromagnetic radiation. It has been concluded that a matched three-port junction containing a lossless nonreciprocal element will behave as a perfect circulator. The performance characteristics of the *Y* circulator at 9 GHz have been described by Chait and Curry [51]. Thaxter and Heller [52] demonstrated the usefulness of this device at millimeter wavelengths and developed units for operation at 4 and 2 mm. A particularly compact version was constructed in a stripline junction at 10 GHz by Davis, Milano, and Saunders (53). The stripline configuration was also used to construct *Y* circulators at frequencies as low as 100 MHz by Buehler and Eikenberg [54], who developed a new approach for shaping the ferrite for high performance and broad bandwidth. Bosma [55] has solved the boundary-value problem for the stripline three-port junction and tried to explain that the circulation depends on both nonreciprocal field displacement and destructive interference.

5) Reciprocal Phase Shifter:

If a magnetized ferrite is placed at the center of a rectangular waveguide, the propagation will be reciprocal. This device is useful for antenna-scanning and switching applications, since large changes in phase can be controlled at high switching speed by changing the magnetic field intensity applied to the ferrite. Heller and Momo [56] made use of the large change in permeability as a function of dc field intensity near ferromagnetic resonance, but they experienced some resonance losses. Bush [57] reported a practical phase shifter which makes use of the small change in permeability that occurs as the ferrite becomes magnetized in a small dc magnetic field. The largest phase shift was demonstrated for a large ferrite rod placed at the center of a rectangular waveguide with the dc magnetic field applied along the direction of propagation. Reggia and Spencer [58] made a thorough experimental study of the reciprocal phase shifter and achieved over 200° of phase shift per inch of ferrite length (at *X* band) as the dc field was changed from zero to about 30 Oe. They also demonstrated the essential fact that large phase shift could be obtained only for relatively large ferrite-rod diameter, i.e., larger than one-fifth of the waveguide width. Clavin [59] showed that slabs of ferrite placed on either the narrow or broad walls of the guide produced reciprocal phase shift but that the effect was very much smaller than that produced by the longitudinally magnetized rod. Bowness [60] and Brown, Cole, and Honeyman [61] have discussed the means of reducing the hysteresis losses experienced in fast switching or scanning operation of the phase shifter.

Reggia and Spencer had obtained their experimental results with the use of a TE_{10} fundamental mode of rectangular waveguide. Rizzi and Gatlin [62] discussed the possibility that some Faraday rotation was involved when the ferrite was large enough to propagate orthogonal TE_{11} modes with the ferrite rod acting as a dielectric waveguide. Clavin [63] also suggested the possibility of the next higher mode TM_{01} being excited. Weiss [64] developed a qualitative theory based on a dielectric-rod waveguide effect, tensor permeability, and Faraday rotation but was unable to make a quantitative comparison with experimental results. Lax and Button [65] and Button and Lax [66] performed a computation of the reciprocal phase shift by using first-order perturbation theory, and their results compared satisfactorily with the experimental characteristics on both a quantitative and qualitative basis without invoking higher order modes, tensor properties, or the Faraday effect. Bowness, Owen, and Thomassen [67] described and demonstrated experimentally the excitation of the cross-polarized TE mode by the tensor properties of the ferrite when the rod is large enough to act as a dielectric waveguide. They used this principle to design the resistance-sheet amplitude modulator. Reggia [68] developed an absorption switch of a similar type based on Tompkins's [69] analysis of the modes in a large ferrite rod.

C. Coaxial-Transmission-Line Components

Carlin [70] and Sucher and Carlin [71] formulated the theoretical solution of the reciprocal ferrite phase shifter in simulated coaxial line by using the parallel-plate analog. Their theoretical results indicated a small amount of nonreciprocal phase shift when the ferrite was so placed as to distort the TEM-mode unsymmetrically. Seidel [72], in his general discussion of ferrite problems using TE modes, described methods of TEM-mode distortion by using dielectric loading to provide an RF field pattern suitable for nonreciprocal ferrite devices in coaxial line. Concurrently, the dielectric-loaded coaxial isolator was demonstrated by Duncan, Swern, Tomiyasu, and Hannwacher [73]. The theoretical field patterns of the distorted TEM mode and the principles of operation of the coaxial nonreciprocal phase shifter were analyzed quantitatively by Button [45] at microwave frequencies and extended by Boyet, Weisbaum, and Gerst [74] to the UHF region. These theoretical evaluations were verified experimentally by Rowley [75].

D. Nonlinear Devices

The magnetic properties of ferrites are not linearly dependent on the RF field intensity at high signal power. This was demonstrated by the resonance experiments of Bloembergen [76], Damon [77], and Wang. This phenomenon had also been observed in waveguide by Sakiotis, Chait, and Kales [78]. This nonlinear phenomenon formed the basis of a concept which ultimately led to such devices as the harmonic generator, microwave power limiter, and the ferromagnetic amplifier.

1) The Harmonic Generator:

The first application of the nonlinear effect came with the invention of the frequency doubler by Ayres, Vartanian, and Melchor [79]. A transversely magnetized ferrite was ordinarily placed at the side or in the center of a rectangular waveguide in a region of maximum (and linearly polarized) RF magnetic field intensity. Pippin [80] showed that the same principles may be applied to achieve frequency mixing. Melchor, Ayres, and Vartanian [81] were able to acquire conversion efficiencies as large as -6 dB with an output of 3 W at 18 Ghz before heating of the ferrite quenched the performance. Stern and Pershan [82] showed theoretically that the output amplitude should be inversely proportional to the resonance line width of the ferrite and directly proportional to the saturation magnetization and the square of the incident microwave-signal intensity. Experiments at a wavelength of 2 mm have been carried out by Ayres [83] and Roberts, Ayres, and Vartanian [84] using both Ferramic G and yttrium–iron garnet. Output of 50 W has been observed at 140 GHz.

2) Ferromagnetic Amplifier:

The nonlinear terms in the equation of motion of the classical spin system give rise to harmonic-frequency generation. Similarly, incident waves of two different frequencies, properly disposed with respect to the dc magnetic field, induce a magnetic moment and, consequently, RF magnetic fields at the sum and difference frequencies of the two exciting radiations. Therefore, one of the obvious extensions of harmonic generation is nonlinear frequency mixing using ferrites. The most interesting extension of this principle has been the ferromagnetic amplifier proposed by Suhl [85], [86] and subsequently demonstrated by Weiss [87], [88]. However, to get amplification or oscillation (not merely frequency conversion at power levels several magnitudes below the power level of the source), a feedback system is required. Suhl described the operation of the amplifier on a theoretical basis in terms of the mutual coupling by the ferrite spin system of three frequencies: the pump, the idler, and the signal frequencies. He visualized three possible methods of operation which he called the electromagnetic, semistatic, and magnetostatic. Berk, Kleinman, and Nelson [89] described a modified semistatic operation using the ferromagnetic-resonance frequency as the idler frequency, and Whirry and Wang [90] demonstrated this method. They achieved 110 dB gain over 1.5 Mc bandwidth at 6 GHz with a noise figure between 11 and 16 dB. These amplifiers required high-intensity pulsed pump power until Denton [91], [92] developed the method of longitudinal pumping with CW power. The pumping power of only 500 mW was applied parallel to the dc biasing field, and the amplifier used two magnetostatic modes for idler and signal frequencies. The amplifier exhibited 25-dB gain with a noise figure of 12-1/2 dB. Damon and Eshbach [93] carried out a theoretical analysis of amplifier performance comparing the gain–bandwidth product of the several methods of operation.

3) Microwave Power Limiter:

Two separate features of the nonlinear phenomenon in ferrites may be used to design power limiters. These are the collapse of the susceptibility at resonance at a threshold RF power level and the rise of a subsidiary absorption peak in the normally low-loss region between zero dc field and the resonance field. DeGrasse [94] utilized the former by coupling crossed striplines with a small sphere of yttrium–iron garnet. At low power levels the tensor susceptibility coupled the crossed lines, but at the threshold power level the susceptibility declined abruptly and the crossed junction reflected the incident power. The subsidiary absorption has been used by Uebele [95], Skomal and Medina [96], and Martin [97] to introduce loss above the threshold power level. These limiters all suffer from the fact, however, that they pass a rather large initial spike; as a result, they are not generally used at high-power levels for crystal protection. The problem of the leakage spike has been solved effectively by Stern [98], who uses a fine metal wire imbedded in the ferrite to concentrate the intense RF magnetic fields within the specimen. Arams, Grace, and Okwit [99] have developed versatile limiters also having a leading-edge spike of short duration.

E. Specialized Applications

In addition to the widely used devices mentioned above, other devices having more-specialized application have been developed. One of the earliest inventions, reported by Reggia [100], was a magnetically controlled coaxial attenuator containing ferrite material. He designed several such attenuators to operate over a broad frequency range. The attenuation characteristics of many different types of ferrites in coaxial transmission line were measured by Reggia and Beatty [101] in the frequency range from 300–3000 Mc.

High-speed microwave switches were also among the early developments in ferrite applications. The first study of this type was made by LeCraw [102], who investigated the high-speed magnetic pulsing of ferrites in circular waveguide. He found that it was possible to construct a microwave switch having a switching time of 12 m·μs. LeCraw and Bruns (103) measured the time delay of the microwave output pulse with respect to the magnetizing pulse. Sullivan and LeCraw [104] described a cavity-type isolation switch which utilized an axial ferrite rod in a cylindrical cavity operating in the TE_{11} mode.

A substantial improvement in traveling-wave-tube operation was obtained by Cook, Kompfner, and Suhl [105], who used the nonreciprocal loss properties of ferrite attenuators for quenching the backward wave. They surrounded the metallic helix with a ferrite helix which was circumferentially magnetized. At about the same time, Rich and Webber [106] demonstrated nonreciprocal attenuation in a helix that was surrounded by a ferrite cylinder magnetized in the direction of the helical axis.

An interesting application of ferrites in rectangular waveguide was made by Damon [107]. He constructed a magnetically controlled directional coupler by extending a ferrite rod through a coupling hole between two waveguides which were placed one directly above the other.

The magnetic tuning of ferrite-loaded rectangular transmission cavities was described in detail by Jones, Cacheris, and Morrison [108]. They applied their results to a study of wide-band and frequency modulation of ferrite-loaded klystrons.

This problem was treated by Fox, Miller, and Weiss [37] by the pointfield approach, and they also suggested field-displacement devices based on these principles. A balanced-stripline isolator was developed by Fix [109], who placed ferrites in the circular field configurations in this type of transmission line and thus obtained nonreciprocal effects.

Ferrites have been applied for antenna-scanning purposes. Angelakos and Korman [110] have studied the properties of radiation from ferrite-filled apertures. Another antenna application has been reported by Reggia, Spencer, Hatcher, and Tompkins [111], who used an array of radiating ferrite rods for scanning. In addition, they discussed the possibilities of their device for high-speed magnetic lobing and for changing the polarization of the radiation field.

1) Birefringence:

The birefringent properties of ferromagnetic media that are magnetized transverse to the direction of propagation were outlined by Polder [13]. At optical wavelengths this phenomenon of double refraction is known as the Voigt and the Cotton–Mouton effect. The initial experimental investigation of double refraction in ferrites was made by Weiss and Fox (112) at 9 and 24 GHz. They also analyzed the phenomenon in terms of the effective permeability given by Polder. The nonreciprocal nature of the birefringence in circular waveguide was indicated by Turner [113]. The first practical application of the birefringent effect was made by Cacheris [114]–[116] who constructed a single-sideband frequency modulator using both mechanical and electrical rotation of a transverse magnetic field to magnetize ferrite rods in circular waveguide at 9 GHz. Du Pre [117], [118] studied the Cotton–Mouton effect on a ferrite disk in circular guide as a function of magnetic field at 9 GHz. Sakiotis [119] reported on the use of double refraction in ferrites for quarter-wave and half-wave plates in circular waveguide. A detailed analysis of the birefringence of ferrite-loaded round waveguide was given by Fox, Miller, and Weiss [37]. Measurements of the birefringence of various ferrite configuration in circular waveguide were made by Karayianis and Cacheris [120] for the purpose of obtaining large differential phase shifts relatively independent of frequency.

2) Tunable Cavities:

The resonant frequency of a cavity containing a small amount of ferrite can be tuned by varying the external dc magnetic field applied to the ferrite. The exact solution for the resonant frequencies as a function of applied field intensity for the completely filled rectangular resonator was given by Heller and Campbell [121], and the TM_{0m0} modes of the filled cylindrical resonator were discussed by Damon and Kouyoumjian [122]. The theoretical solution of the partially filled cavity is normally very difficult. Heller [50] furnished the solution for the TM_{0m0} mode in the partially filled cylindrical cavity and pointed out that the TM_{lm0} modes of the cylindrical resonator containing an axially magnetized ferrite rod have a relatively simple solution. The problem was formulated by both Bussey and Steinert (123) and Heller (124). The latter worked out results for several TM_{lm0} modes, plotted RF field patterns, and compared the results of the TM_{010} mode with experiment.

F. Performance of Ferrite Devices

Nearly all of the basic ferrite devices were originally designed to operate in microwave bands between 5 and 10 GHz. Attempts to adapt these components to lower frequencies were frustrated by a deterioration in performance and also by low-field losses. The latter were caused by incomplete magnetization of the ferrite in the smaller dc fields required for resonance effects at frequencies below about 5 GHz. The very large dc magnetic fields required to achieve resonance at very high frequencies, say at 30 GHz and above, were inconvenient to supply in ordinary applications. The components were also constrained to operate at low RF power levels to avoid heating of the ferrite specimen and also to prevent the onset of high-power instabilities.

The performance of the original devices themselves was not entirely satisfactory. The devices suffered from nattor bandwidth. Furthermore, the figure of merit of both the isolators and circulators was not impressive. These problems were solved through the improvement of experimental techniques, a theoretical understanding of high-power effects, and the development of a general theory of propagation of waveguide modes in ferrite-loaded waveguide using perturbation theory.

1) Perturbation-theory Evaluation: The theoretical evaluation of ferrite waveguide devices in terms of fundamental ferrite and waveguide parameters is very complicated and does not yield explicit results. Lax [33] developed an explicit expression for the figure of merit of the Faraday rotator by adapting the cavity-perturbation theory of Lax [29] and Berk [28] to waveguide problems. Lax [32] extended this approach to develop figures of merit for the resonance isolator and nonreciprocal phase shifter. These were simple relations expressing the reverse-to-forward ration of attenuation of an isolator (or the nonreciprocal phase shift per unit attenuation for a phase shifter) in terms of the ferromagnetic-resonance frequency, the ferromagnetic-resonance line width of the specimen, and the gyromagnetic ratio.

2) Components at Ultrahigh Frequencies: The design of ferrite components to operate at low microwave frequencies and in the UHF region of the spectrum has required the use of specially doped ferrites and garnets. The early devices were built to operate at 9 GHz prior to the development of the new materials. The lower frequency limit was then in the vicinity of 3 GHz. The first successful attempt to operate below X band was reported by Rowen [25], who measured the nonreciprocal attenuation of a resonance isolator from 6 to 7 GHz. An *S*-band resonance isolator was built by Chait [38] to operate in rectangular waveguide at about 3 GHz. One of the earliest resistance-sheet isolators was designed by Fox, Miller, and Weiss [37] for 6-GHz operation.

Three principal obstacles to low-frequency operation became evident. One of them is the modest increase in dielectric loss experienced in polycrystalline materials as the frequency is reduced. A much more serious limitation is the low-field magnetic loss experienced in material not completely magnetized by the small dc field required for resonance at low frequencies. Polder and Smit [125] identified this loss as the natural ferromagnetic-resonance loss in internal fields caused by domains and anisotropy which has previously been demonstrated by Rado, Wright, and Emerson [126]. The latter interpretation has been verified by Pippin and Hogan [127] Polder and Smit showed that the maximum frequency to which low-field losses extend is proportional to the saturation magnetization of the ferrite. Fox and Lax [128] and Fox [129] investigated the possibility of extending dispersive ferrite devices to the 500- to 3000-Mc range by using a magnetic biasing field larger than that required for resonance. Such larger fields tend to saturate the ferrite, remove domains, and eliminate this source of low-field loss. Such a circulator was constructed at 3 GHz by Stern. Van Uitert, Schafer, and Hogan [130] reduced the magnitude of the saturation magnetization of magnesium ferrites by aluminum substitution, thereby enabling the operation of dispersive devices to be extended to lower frequencies. Their measurements were made at 4 GHz. Van Uitert [131] discussed the properties and preparation of such low-magnetic-saturation ferrites, and Suhl, Van Uitert, and Davis [132] studied the resonance properties at UHF. Cacheris and Sakiotis [133] have designed high-performance, low-loss stripline phase shifters at 300 Mc by taking the opposite point of view. They use high-magnetization ferrites and operate at a frequency less than that at which the natural resonance appears.

In the design of conventional devices, however, a third obstacle remained. The performance (figure of merit) of a given device declined if the physical parameters were simply scaled proportionately for operation at lower frequencies. Lax [32], [33] defined the figure of merit as the reverse-to-forward ratio of attenuation for an isolator and as the nonreciprocal phase shift per unit of attenuation for dispersive devices. The theoretical expressions for these figures of merit showed that UHF operation would be greatly improved if there could be found materials having narrower resonance lines than the commercial polycrystalline ferrites available at the time. Heller and Catuna [134] verified this by constructing a resonance isolator at 1300 Mc and showing the superior performance of a model using a ferrite having narrower resonance line width and lower saturation magnetization. Isolators soon became generally available at frequencies as low as 200 Mc; they used low-magnetization ferrites doped with aluminum and yttrium–iron garnet doped with gallium.

The problem of the large size and weight of UHF devices has been alleviated through the use of cut-down rectangular waveguide and the design of coaxial and stripline models. A substantial advance occurred, however, when Seidel (135) described the possibility of a lumped circuit isolator. Cacheris and Sakiotis (133) worked out the theory in detail and constructed a miniature high performance isolator to operate in the 300- to 500-Mc range although it is only an inch thick and weighs just a few ounces.

3) Components at Millimeter Wavelengths Conventional ferrite isolators designed to operate at a wavelength of 8 mm required an external dc magnetic field of 10 kG. Beljers [136] found that the hexagonal magnetoplumbite called Ferroxdure has an internal anisotropy field of 17 kG and that resonance occurs at millimeter wavelengths in this internal field. Resonance in the class of materials was investigated further by Weiss and Anderson [137] and by Du Pre, De Bitetto, and Brockman [138]. Resonance isolators were built by Weiss and Dunn [139] at 5 mm and by Kravitz and Heller [140] at 4 mm.

Dispersive devices using conventional ferrites can be built because large magnetic fields are not required. Thaxter and Heller [52] were to adapt the three-port circulator to operate at 4 and 2 mm. The external field required was very small, and the insertion loss was much less than 1/2 dB.

Promising advances were being made in the millimeter and submillimeter region based on Foner's (141) suggestion for the use of the large internal fields of antiferromagnetic materials for nonreciprocal devices. Heller and Stickler [142] have described the principles of operation of antiferromagnetic devices and have demonstrated the operation of isolators at 2 mm.

Acknowledgment

This historical review was prepared from a comprehensive literature survey personally by the author who takes the appropriate responsibility for the accuracy and completeness. There is no space available in a short review of this massive subject for personal opinions and reminiscences. The length of the manuscript was not limited by omissions of references on the basis of relative significance based upon this writer's prejudice. The length was limited by restricting the scope of the topic to the first ten years of microwave applications with a short introduction dealing with the nature of the ferrites themselves. The manuscript would have been approximately five times longer if the full history of ferrite materials development, ferromagnetic resonance and nonlinear phenomena, theoretical development and improvements in performance were added. No reference has been made to events of the past 25 years which has left the author free of that constant worry that he may offend his friends by inadvertent omission of their most treasured reference. Special reference must be made, however, to the author's best friend, Professor Benjamin Lax of M.I.T., Cambridge, whose book, *Microwave Ferrites and Ferrimagnetics* covers this topic completely.

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Kenneth J. Button (SM'60–F'82) did undergraduate and graduate work in physics at the University of Rochester after serving for four years in the U.S. Army Infantry during WW II.

He joined Benjamin Lax in 1952 at the new M.I.T. Lincoln Laboratory to begin some of the pioneering work that led to the book *Microwave Ferrites and Ferrimagnetics*. As solid-state physicists, they demonstrated the use of magnetic fields in the measurement of the electronic properties of semiconductors. In 1962, they opened the new M.I.T. National Magnetic Laboratory.

Mr. Button has served six years on the IEEE-MTT Administrative Committee. He received their Distinguished Service Award in 1980, and their Certificate of Recognition in 1981. He was Vice-President of the IEEE Quantum Electronics Society, President of the New England Section of the Optical Society, on the Board of Directors of the Massachusetts Engineers' Council, and a member of the IEEE Energy Committee. He is Chairman of Commission D (Physical Electronics) of the International Union of Radio Science (URSI). He is the organizer of the annual Conference on Infrared and Millimeter Waves and the Editor of an Academic Press series of books and a Plenum Press Journal, both entitled *Infrared and Millimeter Waves*. He is a Fellow of the American Physical Society.