"distort" it to obtain a direct coupled cavity filter with a predictable performance. Some examples were analyzed numerically, and the predicted performance was closely confirmed.

This method is usually tedious to synthesize a filter *ab initio*, but it is quite easy to use in reverse, *i.e.* to derive the quarter-wave transformer prototype from a direct coupled cavity filter which has already been designed by another method. This was found to lead to a quick and accurate evaluation of its performance. If this predicted performance turns out to be inadequate, the filter can then be redesigned as illustrated in this paper.

ACKNOWLEDGMENT

The author is very grateful for the help, always freely given, of Dr. W. H. Huggins, Dr. F. Hamburger, Jr., and Dr. C. F. Miller, of the Johns Hopkins University. Much of the numerical work was done by A. C. Robertson under the guidance of W. M. Etchison.

Most of the ideas for this paper originated during design work done at Westinghouse, and this investigation was made possible by the financial assistance of the Westinghouse Electric Corp.'s B. G. Lamme graduate scholarship during the academic year 1958–1959.

Broad-Band Ridge Waveguide Ferrite Devices*

E. S. GRIMES, JR.†, MEMBER, IRE, D. D. BARTHOLOMEW†, D. C. SCOTT†, MEMBER, IRE, AND S. C. SLOAN†, MEMBER, IRE

Summary—**The design and development of a medium CW power level, 1.57:1 bandwidth, quadruply-ridged circular waveguide Faraday rotator and two high CW power, 2:1 bandwidth, double ridge rectangular waveguide isolators are discussed.**

The rotator is designed in quadruply-ridged circular waveguide with a ferrite configuration somewhat different from that proposed by other investigators. It can be made to exhibit broadband rotation and large rotation per unit length of ferrite section, and may be used in most medium CW power level applications. Forty-five degree rotation is achieved over the 7.0-kMc to 11.0-kMc band.

The isolators operate from 2.0 kMc to 4.0 kMc in DR-37 waveguide and from 3.8 kMc to 7.6 kMc in D-34 waveguide respectively. The reverse to forward wave attenuation ratio exceeds 10.0 db to 1.0 db for both isolators.

INTRODUCTION

THE development of microwave components with operating bandwidths in excess of previously established maximums has been necessitated by the requirements of modern microwave systems. Perhaps the most widely used method for maintaining good performance characteristics of a microwave component over a large operating bandwidth is to reduce the variation of guide wavelength with frequency. The guide wavelength for any air-filled microwave transmission line is determined from the formula

$$\lambda_g = \frac{\lambda}{\sqrt{1 - (\lambda/\lambda_c)^2}},$$

where

λ = operating wavelength
λ_g = guide wavelength
λ_c = cutoff wavelength.

Thus, for operating frequencies far above the cutoff frequency the variation in guide wavelength with frequency is greatly reduced. This condition can be brought about in circular and rectangular waveguides by using ridges protruding into the guide, thus lowering the dominant mode cutoff frequency without appreciably affecting the next higher mode cutoff frequency.[1,2] There, the resultant increase in bandwidth of the transmission line allows operation far above cutoff.

It is the purpose of this paper to present design information on a quadruply-ridged circular waveguide Faraday rotator and two double-ridge rectangular waveguide isolators.

FARADAY ROTATOR

A number of techniques have been proposed for maintaining rotation constant with frequency. In terms of maximum bandwidth the most successful ones known to the authors have utilized quadruply-ridged wave-

* Received by the IRE, November 4, 1959; revised manuscript received, May 10, 1960. This paper was presented at the PGMTT National Symposium, Cambridge Mass., June 1–3, 1959. The work was supported by the U. S. Air Force Wright Air Dev. Center under Contract No. AF30(600)35477.

† Sperry Microwave Electronics Co., Div. of Sperry Rand Co., Clearwater, Fla.

[1] S. B. Cohn, "Properties of ridge waveguide," PROC. IRE, vol. 35, pp. 783–788; August, 1947.

[2] S. A. Schelkunoff, "Electromagnetic Waves," D. Van Nostrand Co., Inc., New York, N. Y., pp. 392–395; 1943.

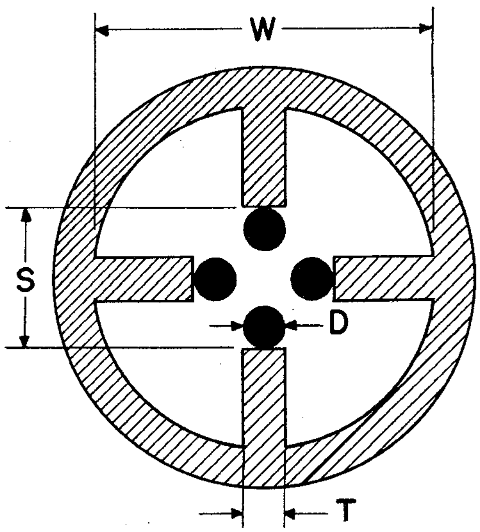


Fig. 1—General quadruply-ridged rotator structure. W=circular guide inside diameter, S=ridge separation, T=ridge thickness, D=ferrite diameter.

guide.[3–5] The general quadruply-ridged rotator described in this paper is shown in Fig. 1. It has a ferrite configuration somewhat different from that proposed by other investigators, in that the usual axially located ferrite rod is replaced by four ferrite rods (or slabs) mounted on the ridge edges. A rotation of forty-five degrees is attained over the 7.0-kMc to 11.0-kMc band without the use of "stagger-tuned" sections.

The variation of rotation with frequency due to changes in ridge separation (S) and ferrite diameter (D) has been measured. During the measurement, the ferrite type and length (L), ridge thickness (T), circular waveguide diameter (W), and axially applied magnetic field (H_a) remained constant. The measurement apparatus was similar to that used by Rizzi.[6] Linear ridge tapers were used with a taper length of 1.50 inches.

The usual considerations were made in establishing the ferrite material. For maximum rotation the highest saturation magnetization possible was chosen subject to the requirement of minimum low field loss. Low dielectric loss tangent and reasonably high Curie temperature were also desired. This suggested the choice of a magnesium manganese ferrite with a saturation magnetization of about 2000 gauss. The rotator configurations to be discussed can operate down to zero field with a low insertion loss. However, the data to be presented were taken with the ferrite in a magnetically saturated condition. To design a fixed low loss rotator, the saturation magnetization could exceed 2000 gauss since operation at zero field would not be required. This would, of course, result in more rotation per unit length than in the configurations presented in this paper.

The effects of ridge separation and ferrite rod diameter on rotation as a function of frequency are shown in the curves of Fig. 2. The insertion loss for all configurations was less than 1.0 db for applied magnetic fields from 0 to 120 gauss. The small fluctuations in rotation are probably caused by mismatches in the rotator structure. Utilizing these basic design curves, it was found empirically that by increasing the ridge taper length to improve the impedance match, and optimizing the ferrite length and diameter, the desired rotation was obtained. The resultant performance, after modifying the structure as outlined, is shown in Fig. 3.

Since the ferrite is located on a metallic ridge, the heat generated due to CW power is dissipated more easily than in most other rotator structures. Furthermore, it has been found that the ferrite rods can be replaced by slabs of equivalent cross-sectional area. Thus, the ferrite can make good thermal contact on the ridge edge.

Although the use of dielectrics was not explored in conjunction with the configuration of Fig. 3, it is believed that broadband forty-five degree rotation over bandwidths in excess of 1.57:1 might be achieved by using them.

The configuration just described may be incorporated in most medium CW power level microwave components using the Faraday rotation principle.

Double-Ridge Isolators

In the design of high CW power isolators it is desirable to place the ferrite against a guide wall so as to assure efficient heat conduction. Such a location also provides a simple means of fixing the ferrite in place. Unfortunately, in air-filled double-ridge waveguide propagating the dominant mode, measurements indicate that the clearly defined regions of circularly polarized magnetic fields required for maximum nonreciprocity do not exist adjacent to a guide wall. Rather, there appears to be a curvature of the circular polarization surfaces and a weak component of the microwave magnetic field at the points where these planes interesect the waveguide walls.

A technique is described herein that allows the ferrite to be positioned on the waveguide ridges where the important advantages of high microwave field intensity, smaller biasing magnet gap (with the attendant reduction in magnet size and weight), efficient heat conduction, and ease of assembly are realized. The general double-ridge waveguide isolator structure is shown in Fig. 4. As indicated, the technique involves positioning a low loss dielectric slab in the area between the ridges extending from one ridge surface to the other. It is then possible to attach the ferrite to the flat areas of the ridges adjacent to the dielectric-air interface and achieve good nonreciprocal attenuation characteristics. This technique, originally proposed by Ahrens at Sperry and subsequently investigated by Swern and

[3] M. L. Kales, "Propagation of Fields Through Ferrite Loaded Guides," *Proc. Symp. Modern Advances of Microwave Techniques*, Poly. Inst. of Brooklyn, Brooklyn, N. Y., pp. 215–228; 1955.

[4] P. H. Vartanian, J. L. Melchor and W. P. Ayers, "Broadbanding Ferrite Microwave Isolators," 1956 IRE Convention Record, vol. 4, pt. 5, pp. 79–83.

[5] H. N. Chait and N. G. Sakiotis, "Broad-band ferrite rotators using quadruply-ridged circular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 38–41; January, 1959.

[6] P. A. Rizzi, "High-power ferrite circulators," IRE Trans. on Microwave Theory and Techniques, vol. MTT-5, pp. 230–237; October, 1957.

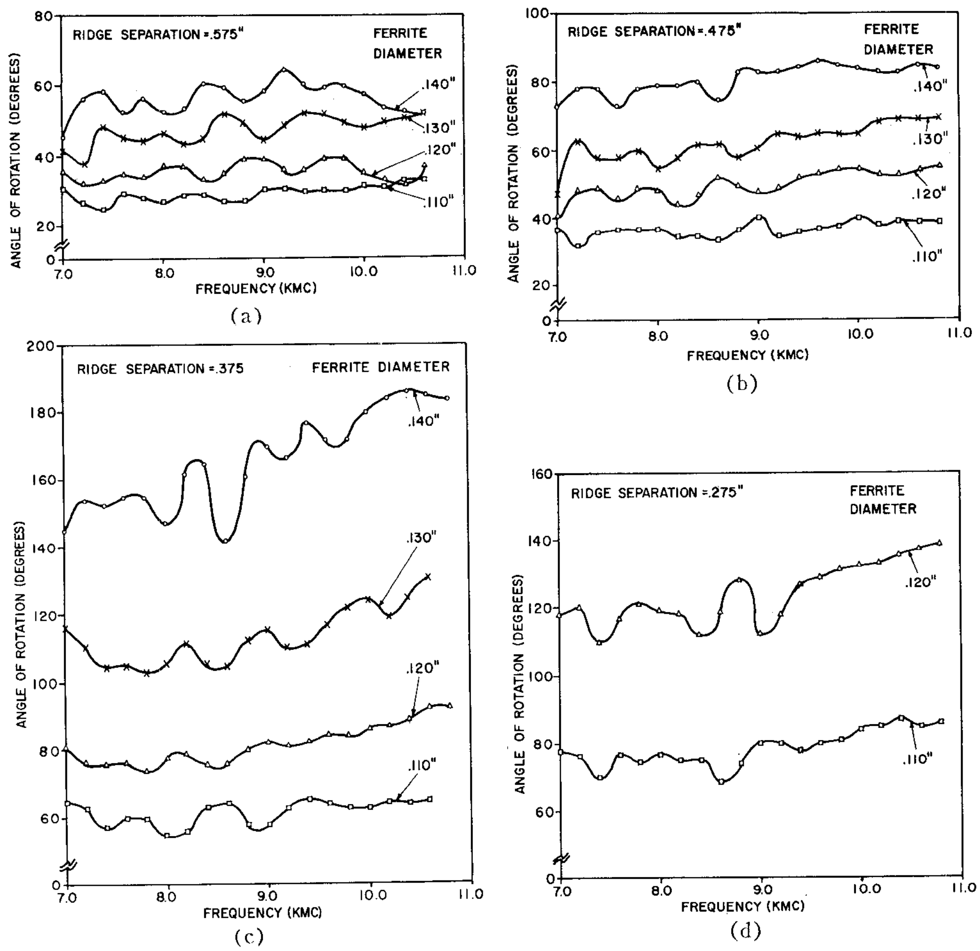


Fig. 2—Angle of rotation vs frequency. Magnesium manganese ferrite, $4\pi M_s=2175$ gauss, $L=3.00$ inches, $H_a=120$ gauss, $W=1.125$ inches, $T=0.125$ inch. (a) $S=0.575$ inch. (b) $S=0.475$ inch. (c) $S=0.375$ inch. (d) $S=0.275$ inch.

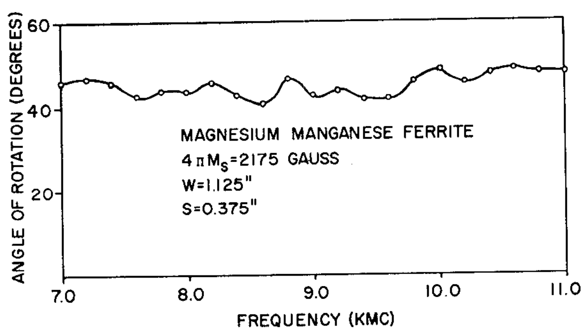


Fig. 3—Angle of rotation vs frequency for final rod configuration.

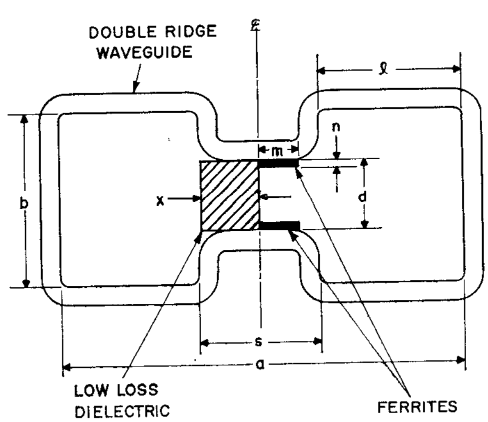


Fig. 4—General double-ridge waveguide isolator structure.

Fleri,[7] is applied in this paper to the design of two high power, 2:1 bandwidth double ridge waveguide isolators in *S*-band and *C*-band. Dielectric loading techniques[8–10] in other transmission lines have been applied successfully in increasing the bandwidth of various devices.

The effects of dielectric constant and dielectric slab width on attenuation ratio were investigated during development. For best results a dielectric constant of about ten (alumina ceramic) and a width of approximately $s/2$ were established. The variation in guide wavelength with frequency is reduced due to the presence of the dielectric.[11] However, the variation in wavelength encountered at the lower operating frequencies is more pronounced in DR-37 and D-34 waveguide due to closer proximity to cutoff.

[7] L. Swern and D. Fleri, "Final Engineering Report Broadband Ferrite Devices Study Program," research sponsored by Air Force Cambridge Res. Center, Air Res. and Dev. Command, Cambridge, Mass., contract no. AF19(604)2248, Sperry rept. no. 7210-13027, May, 1958. AFCRC-TR-58-138 ASTIA document no. AD-152392.

[8] E. A. Ohm, "A broad-band microwave circulator," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 210–217; October, 1956.

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

[10] P. H. Vartanian, W. P. Ayres, and A. L. Helgesson, "Propagation in dielectric slab loaded rectangular waveguide," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 215–222; April, 1958.

[11] D. J. Sullivan and D. A. Parkes, "Stepped transformers for partially filled transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 212–217; March, 1960.

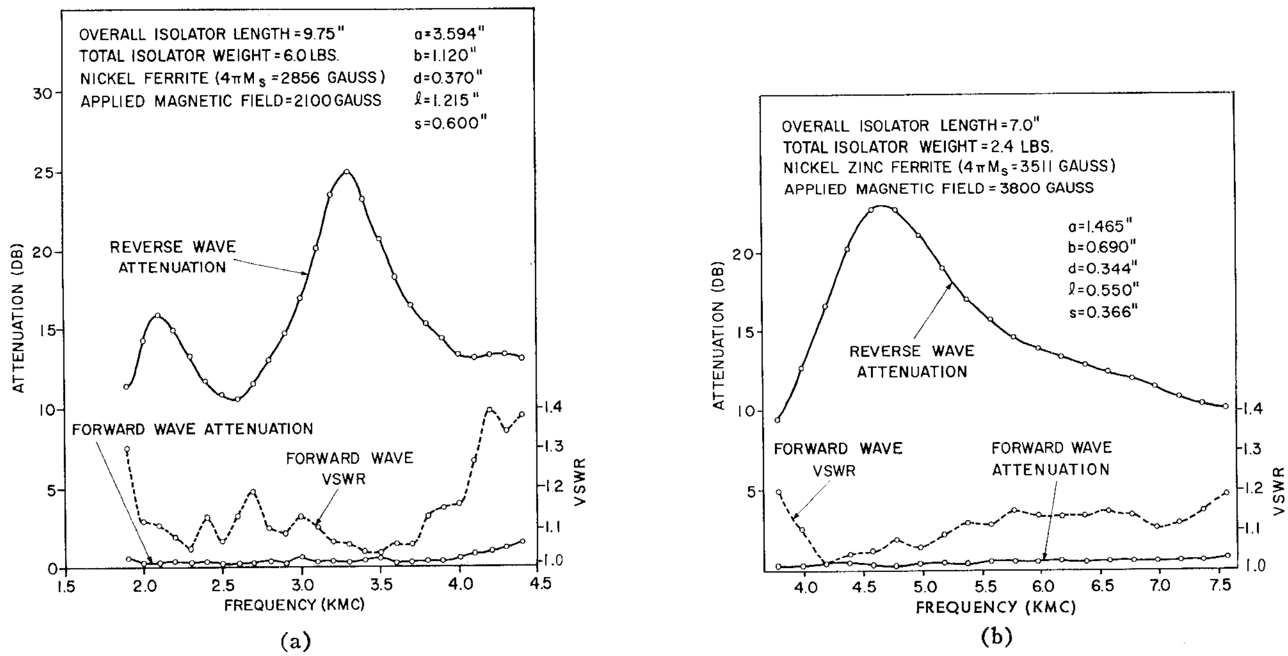


Fig. 5—Performance curves of isolators in (a) DR-37 and (b) D-34 waveguide.

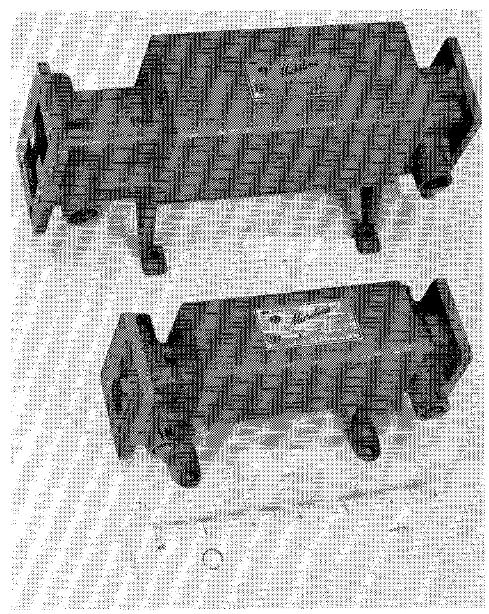
The ferrite types were chosen to have a high $4\pi Ms$ for maximum activity, consistent with low field loss considerations, high Curie temperature and operation over the required bandwidth. The ferrite aspect ratio (m/n) was chosen to be as large as possible for maximum heat dissipation area consistent with minimum forward wave attenuation.

The performance characteristics for the DR-37 and D-34 isolators at room temperature and low power are shown in Figs. 5(a) and 5(b) respectively. An increase in VSWR is indicated for both units at the lower operating frequencies due to proximity to cutoff and the dielectric transition mismatch. It is fully anticipated that, with additional development, the operating bandwidth of the DR-37 isolator can be made to cover the 2.0-kMc to 5.0-kMc frequency range. High CW power measurements on both isolators at room temperature and atmospheric pressure indicate satisfactory operation up to 200 watts. At low power, both units maintain good performance characteristics over the ambient temperature range from −55°C to +125°C. Photographs of the operative liquid cooled isolators are shown in Figs. 6(a) and 6(b).

The nonreciprocal structure described here may also be applied to other ferrite devices designed in double ridge waveguide.

Conclusions

It has been shown that a medium CW power level Faraday rotator with ferrite rods or slabs on the ridge edges can be made to exhibit forty-five degree rotation over a 1.57:1 bandwidth. Also the design of 2:1 bandwidth, high CW power large attenuation ratio isolators in DR-37 and D-34 double ridge waveguide has been proven feasible by the judicious use of dielectric loading. The inherent simplicity of these rotator and isolator structures lend themselves to straight-forward assembly procedures and are rugged enough to withstand reasonable shock and vibration while providing excellent heat transfer properties.



(a)

(b)

Fig. 6—Typical isolator in (a) DR-37 and (b) D-34 waveguide.

Acknowledgment

The authors are grateful to B. J. Duncan for his suggestions during the course of this work and to Dr. J. E. Pippin for his advice during the preparation of this paper.