Broad-Band Ferrite Rotators Using Quadruply-Ridged Circular Waveguide*

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Summary—It has been shown that the rotation of the plane of polarization of a wave propagating in a magnetized unbounded ferrite medium should be independent of frequency. However this is not the case when a ferrite rod of small diameter is placed within a waveguide. For example, if a ferrite rod one-quarter inch in diameter in a fifteen-sixteenth inch diameter circular waveguide is used, the rotation will change by a factor of four to one over the frequency band from 8000 to 10,000 mc. This variation in rotation is substantially due to the waveguide characteristics, and can be minimized by lowering the cutoff frequency of the waveguide.

Various methods of lowering the cutoff of circular waveguide are compared. Data on the broadbanding of the rotation by dielectric loading and also by the use of quadruply-ridged circular waveguide is shown. An experimental study showing the effect of the ridge width and height on the cutoff of the circular waveguide and the frequency dependence of the rotation is discussed.

FERRITE rotators have found wide application in a number of microwave devices. They are used as isolators, phase shifters, switches, modulators, duplexers, etc. In most of these applications it is highly desirable that the rotation be constant over the operating bandwidth of the device. This paper describes some of the propagation studies carried on to determine the dependence of the rotation on various parameters of the waveguide configuration.

The infinite medium theory predicted that the rotation of the plane of polarization of an electromagnetic wave passing through a magnetized ferromagnetic medium should depend on the path length through the medium, the dielectric constant, the permeability, and the magnetization of the medium. It is also predicted that the rotation would be independent of the frequency.[1]

During the early phases of ferrite research it was thought that this infinite medium theory would apply in the case of guided wave propagation. In the center of a circular waveguide there are only transverse components of E and H, and the wave is similar to that of the infinite medium. However, it was found experimentally that rotation increased with frequency.[2]

A number of methods have been used to obtain a rotation constant with frequency. For example, two oppositely magnetized rods of different diameters or different ferrite materials can be selected so that the difference in rotation (*i.e.*, the net rotation) remains more nearly constant with frequency. It is also possible to use a rod whose rotation increases with frequency in combination with a rod whose rotation decreases (negatively) with frequency. Both these methods have the disadvantage of higher loss, since an extra ferrite rod is required and both use larger magnets.

A theoretical analysis of the propagation characteristics of the partially filled circular waveguide is very difficult and no exact numerical solution of the problem is available. However a perturbation theory for rods of small diameter has been derived by a number of workers.[3] The rotation per unit length,

$$\frac{\theta}{L} = 0.22\gamma 4\pi M\left(\frac{r_1}{r_0}\right)^2\sqrt{1-\left(\frac{f_c}{f}\right)^2}\cdot\left[\frac{1}{1-\gamma^2\left(\frac{H+2\pi M}{b}\right)^2}\right]. \tag{1}$$

γ = gyromagnetic ratio (2.8 megacycles per orested)
M = Magnetization
r_1 = radius of ferrite rod
r_0 = radius of waveguide
f_c = cutoff frequency of the waveguide
f = operating frequency
H = applied magnetic field.

This equation shows that the rotation does indeed depend on the frequency, since the frequency appears in two terms of the equation. The frequency dependence of the rotation is determined, first, by how close the operating frequency is to the cutoff frequency of the waveguide, and, second, by how the ferrite characteristics change with frequency. It is evident that the rotation can be made more constant by lowering the cutoff frequency of the waveguide in relation to the operating frequency. This equation was used to calculate the change in rotation with frequency for waveguides which cut off at 6000 and 7500 mc. Fig. 1 shows the results of this calculation. If, for example, one needed a rotator which could be used from 8000 to 10,000 mc and the waveguide cut off at 7500 mc, the rotation would change from 0.48 to 0.805 or 1.68 to 1. On the other hand, if a waveguide that cut off at 6000 mc was used, the rotation would change from 0.91 to 0.97 or 1.065 to 1, a rather substantial improvement. In addition, the rota-

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[1] C. L. Hogan, "The ferromagnetic Faraday effect at microwave frequencies and its applications—the microwave gyrator," *Bell Sys. Tech. J.*, vol. 31, pp. 22–26; January, 1952.

[2] N. G. Sakiotis and H. N. Chait, "Ferrites at microwaves," PROC. IRE, vol. 41, pp. 87–93; January, 1953.

[3] A. A. Th. M. Van Trier, "Guided electromagnetic waves in anisotropic media," *Appl. Sci. Res. Bulletin*, vol. 3, pp. 305–371; 1953.

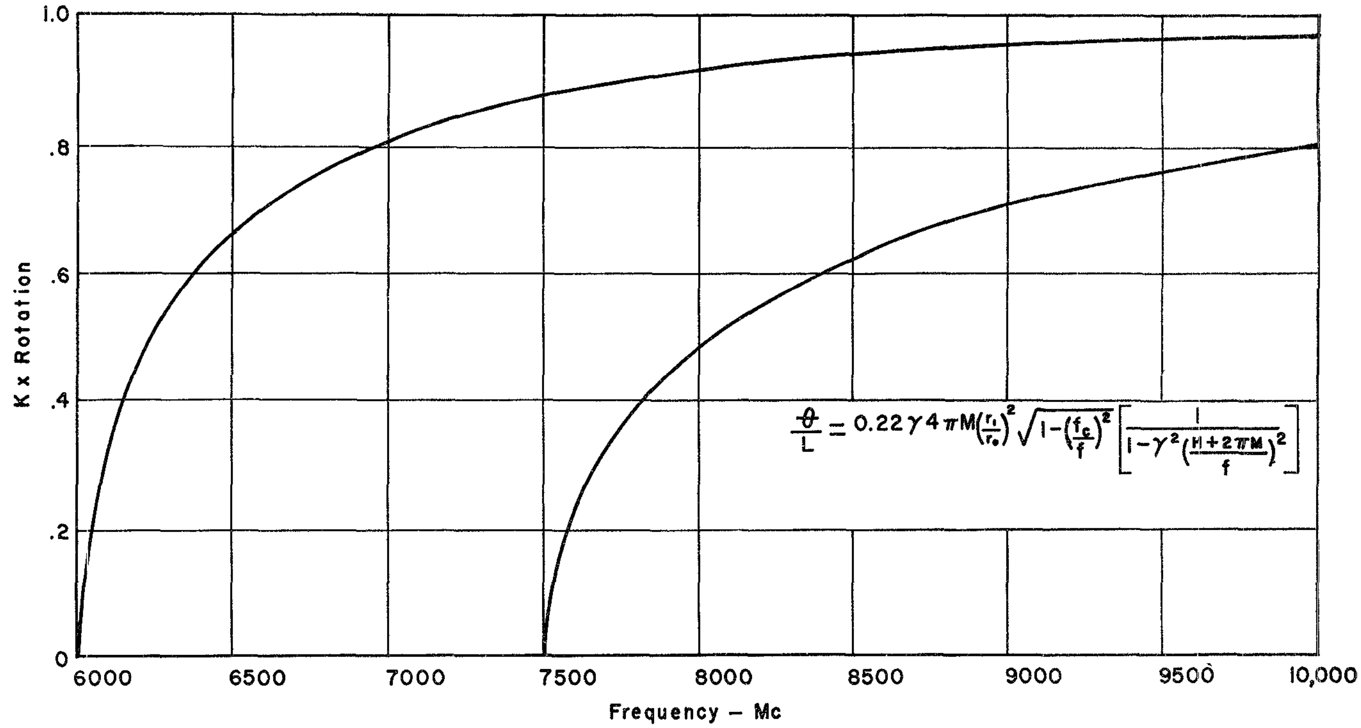


Fig. 1—Rotation vs frequency curves for cutoff frequencies of 6000 and 7500 megacycles.

TABLE I

WAVEGUIDE 15/16 INCH DIAMETER ($\lambda_c' = \sqrt{\epsilon}\,\lambda_c$)

ϵ	1	2.1	5	10
λ_c	4.06 cm	5.89 cm	9.07 cm	12.86 cm
f_c	7400 mc	5100 mc	3310 mc	2340 mc
$R = \dfrac{\text{ROT.@9800 mc}}{\text{ROT.@7400 mc}}$	$\dfrac{95}{20} = 4.75$	$\dfrac{165}{60} = 2.75$	$\dfrac{140}{75} = 1.87$	$\dfrac{110}{50} = 2.2$

tion per unit length would be increased from 0.48 to 0.91 at 8000 mc, and from 0.805 to 0.97 at 10,000 mc.

The first method of lowering the cutoff was to fill the waveguide with dielectric material. Although the rotation became more nearly constant, by about 2.5 to 1, the magnitude of the rotation did not seem to increase as predicted by the perturbation formula. Row R of Table I shows a summary of some of the data, the best being $\epsilon = 5$. However it is possible that better results could be obtained by using a dielectric constant between $\epsilon = 2.1$ and $\epsilon = 5$. Ripples on the curves for $\epsilon = 5$ and 10 indicated trouble from higher modes which could propagate in the dielectric loaded waveguide. Therefore, it was thought that this performance could be improved still further by utilizing a waveguide which had a lower cutoff for the dominant mode but did not substantially reduce the cutoff for the next higher mode. This can be accomplished by the use of ridged guide.[4] On the other hand, in the case of the dielectric-filled guide, all of the cutoffs have been lowered by the same percentage.

Even though the perturbation formula for the rotation was not derived for the case of the ridged guide, it was hoped that qualitatively the results might still apply. This turned out to be the case.

In order for the waveguide to support a circularly polarized mode, the waveguide configuration should present the same appearance to two orthogonal linearly polarized modes. For this reason, a structure utilizing two sets of orthogonal ridges was chosen. Data on ridges in circular waveguide was available only for the case of a pair of ridges. It was therefore necessary that a program of measurement of the cutoff of quadruply-ridged circular waveguide be undertaken. A number of sections of ridged waveguide were built having the dimensions shown in Table II.

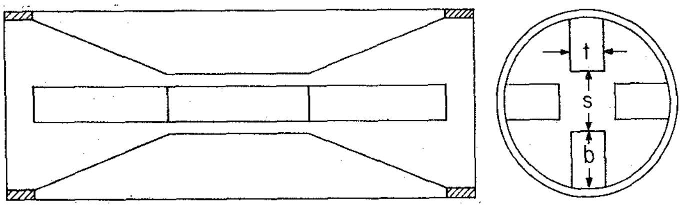
The guide wavelength of these sections was measured at a few frequencies and then the cutoff was calculated from the formula

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{\lambda_c}\right)^2}}. \tag{2}$$

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

[4] M. L. Kales and H. N. Chait, "Ridged Waveguide Rotator," Naval Res. Lab. Progress Rep.; August, 1954.

TABLE II



t	b	s	b	s	b	s	b	s
1/16	7/32	1/2	9/32	3/8	5/16	5/16	11/32	1/4
1/8	7/32	1/2	9/32	3/8	5/16	5/16	11/32	1/4
3/16	7/32	1/2	9/32	3/8	5/16	5/16	11/32	1/4

Waveguide diameter = 15/16.

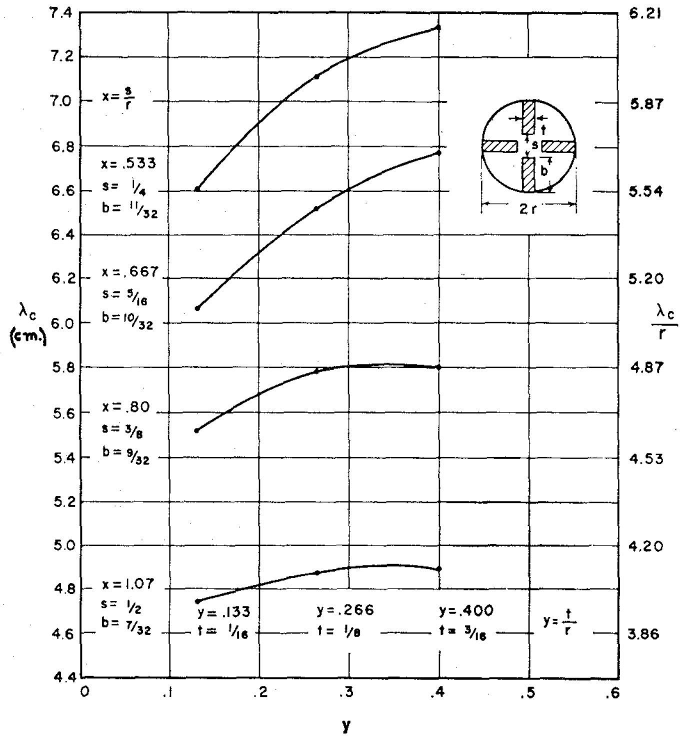


Fig. 2—The dependence of the cutoff wavelength on the dimensions of the ridged waveguide.

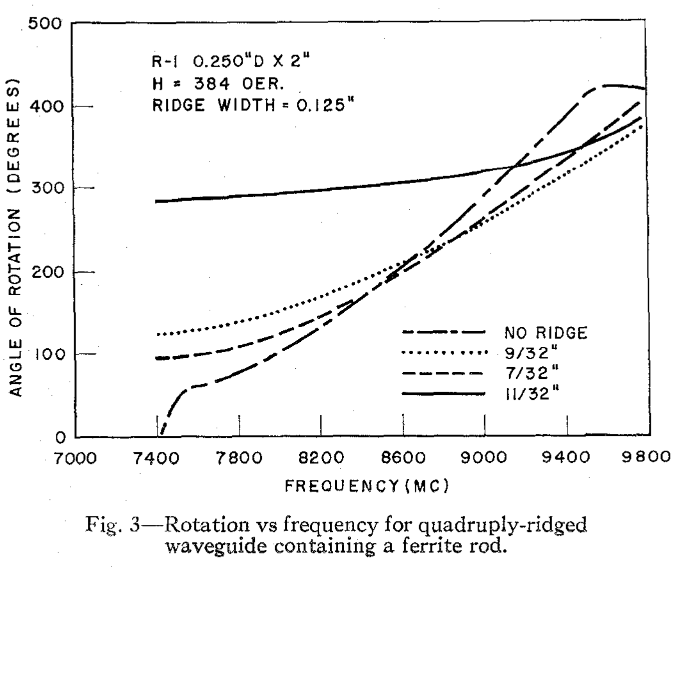


Fig. 3—Rotation vs frequency for quadruply-ridged waveguide containing a ferrite rod.

The results are plotted on Fig. 2. As shown, the cutoff wavelength of the guide can be lowered from 4.06 cm (7390 mc) to 7.3 cm (4110 mc) by the choice of the proper ridges.

The rotation vs frequency at different applied fields was measured for each of the ridged sections containing ferrite rods. Fig. 3 shows a typical set of curves.

Data was taken on samples of R-1, 0.250, 0.225, and 0.200 inch in diameter as well as Trans Tech 390, 0.253 OD by 0.125 ID in each of the ridged sections. Table III shows some of the results of ridges $\frac{1}{8}$ inch thick.

TABLE III

$H = 384$ oer

	Ridge width	Ridge depth	$R = \frac{\text{Rotation at 9800 mc}}{\text{Rotation at 7400 mc}}$
R-1 0.250 D×2 inch	0	0	$\frac{425}{50} = 8.5$
	1/8	7/32	$\frac{400}{100} = 4.0$
	1/8	9/32	$\frac{365}{130} = 2.81$
	1/8	11/32	$\frac{385}{280} = 1.38$
R-1 0.225 D×2 inch	0	0	$\frac{270}{25} = 10.8$
	1/8	7/32	$\frac{245}{75} = 3.3$
	1/8	9/32	$\frac{240}{95} = 2.5$
	1/8	11/32	$\frac{275}{215} = 1.28$
R-1 0.200 D×2 inch	0	0	$\frac{95}{20} = 4.75$
	1/8	7/32	$\frac{105}{35} = 3.0$
	1/8	9/32	$\frac{120}{55} = 2.18$
	1/8	11/32	$\frac{165}{115} = 1.44$
TT 390 0.253 OD×0.125 ID×2 inch	0	0	$\frac{125}{5} = 25$
	1/8	7/32	$\frac{100}{50} = 2$
	1/8	9/32	$\frac{100}{70} = 1.43$
	1/8	10/32	$\frac{105}{85} = 1.24$
	1/8	11/32	$\frac{100}{90} = 1.11$

It is evident from this data that lowering the cutoff of the waveguide by the use of ridges does indeed produce the two changes predicted by the perturbation equation, even though the ferrite rods used were not small. Substantial improvement in the constancy of the rotation and the rotation per unit length are obtained.

A logical conclusion would be to combine the ridges and the dielectric loading. A section of guide was built using the $\frac{1}{8}$ inch$\times\frac{7}{32}$ inch ridges surrounded with poly ($\epsilon=2.56$). Whereas the ridges alone gave a 2 to 1 variation in rotation, the combination was 1.6 to 1, with, however, a reduction in the rotation per unit length.

The losses of the various combinations studied were so low that they could not be measured with sufficient accuracy to determine a merit figure.

Fig. 4 shows the results obtained on the broadbanding of a 90 degree rotator from 8000 to 9600 mc. A cylinder of TT-390, 0.253 OD$\times$0.125 ID $\times$2 inch long was used in the $\frac{1}{8}$ inch$\times\frac{11}{32}$ inch ridged waveguide. The rotation is constant within 2 per cent over the entire frequency range.

The propagation studies have shown that the perturbation theory is qualitatively applicable even in cases where the perturbation may be quite large. The results indicate that the quadruply loaded ridged circular waveguide with or without dielectric loading offers a very good transmission path for broadband rotation devices used in low peak power or in CW applications.

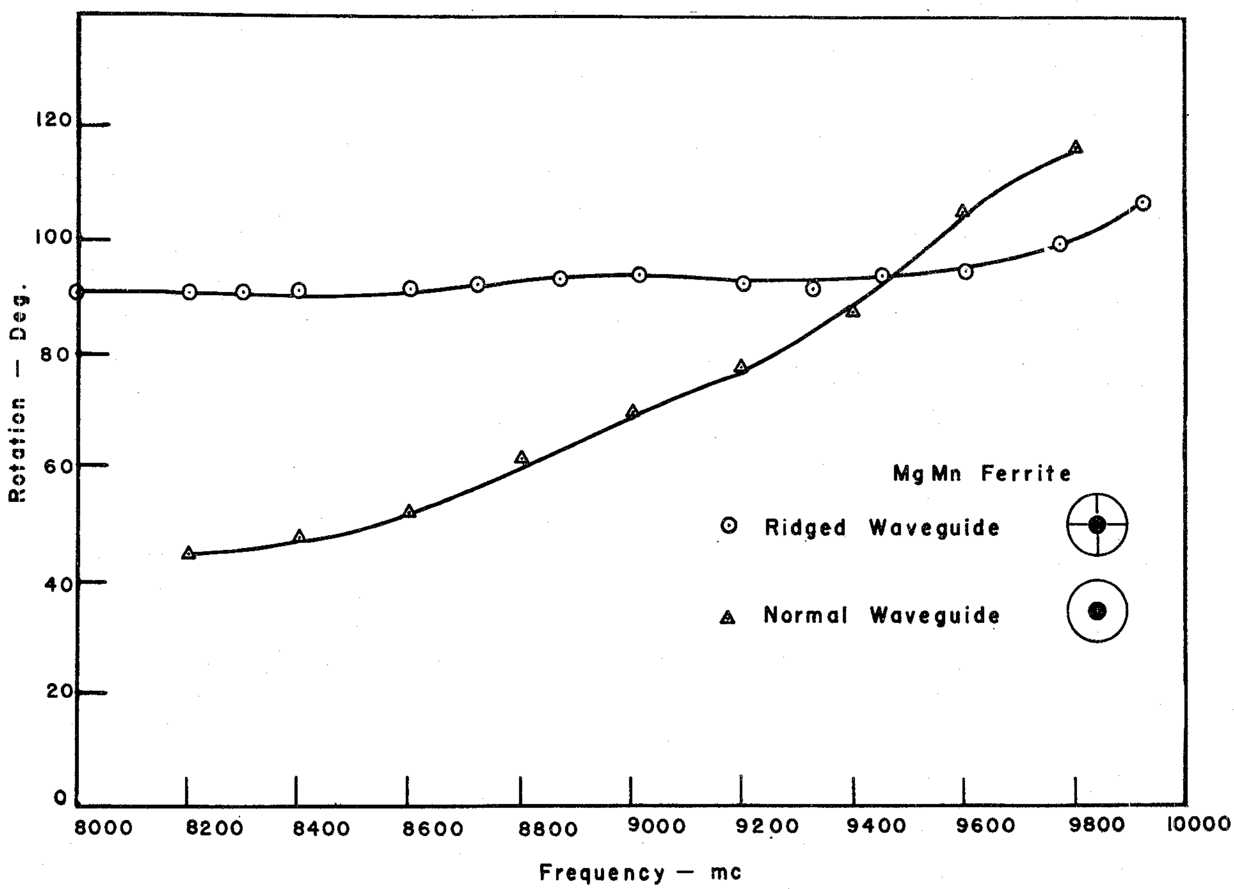


Fig. 4—Rotation vs frequency of a 90-degree rotator with and without ridges.